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**PRINCIPLES  
OF  
NUCLEAR  
PHYSICS**

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**ATOMIC WEAPONS  
TRAINING GROUP  
FIELD COMMAND, DASA  
SANDIA BASE, ALBUQUERQUE, N. M.  
24 MARCH 1960**

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**ERRATA SHEET  
FOR  
PRINCIPLES OF NUCLEAR PHYSICS  
Dated 24 March 1960**

**Page 180, paragraph 155, b (2); change "1.16" to read "1.6."**

**19 April 1960**

## FOREWORD

This publication, Principles of Nuclear Physics, has been issued as a source of background information for students attending the nuclear courses of the Atomic Weapons Training Group, DASA. Students whose training in physics is incomplete, or who lack an understanding of the unclassified aspects of nuclear phenomena as revealed by modern research, will find the information in this publication of value in comprehending course material.

Because this publication deliberately has been slanted toward a specific objective, it makes no claim of being exhaustive or all-inclusive. Instructors will be glad to recommend standard texts available from the Atomic Weapons Training Group, when further information is required.

Users of this publication are invited to report any errors, discrepancies, or omissions they might find. Suggestions for the improvement of future editions will be welcomed.

*Samuel E. Otto*

SAMUEL E. OTTO  
Colonel, US  
Deputy Chief of Staff  
Atomic Weapons Training

## TABLE OF CONTENTS

		<u>Paragraph</u>	<u>Page</u>
<b>CHAPTER 1</b>	<b>MATHEMATICAL PRELIMINARIES</b>		
<b>Section I</b>	<b>Algebra</b>		
	General	1	1
	The Use of Symbols	2	1
	Equations	3	2
	Negative Numbers	4	4
	Exponents and Logarithms	5	5
<b>Section II</b>	<b>Slide Rule</b>		
	General	6	9
	Multiplication	7	9
	Division	8	9
	Powers	9	10
	Slide Rule Practice Problems	10	10
<b>CHAPTER 2</b>	<b>BASIC PHYSICS PRELIMINARIES</b>		
<b>Section I</b>	<b>General</b>	11	12
<b>Section II</b>	<b>Force, Mass, Acceleration</b>		
	Force	12	12
	Mass	13	12
	Acceleration	14	12
	Standards of Mass	15	13
	Weight	16	13
	Momentum	17	15
	Problems	18	15
<b>Section III</b>	<b>Work, Power, and Energy</b>		
	Work	19	16
	Power	20	16
	Energy	21	17
	Problems	22	19
<b>Section IV</b>	<b>Heat Energy</b>		
	Heat and Temperature	23	19
	Specific Heat	24	20
	Thermal Expansion	25	20
<b>Section V</b>	<b>Kinetic Theory</b>		
	Molecular Motion	26	20



		<u>Paragraph</u>	<u>Page</u>
<b>Section V</b>	<b>Kinetic Theory</b>		
	Definitions	27	21
	Kinetic Theory	28	21
	Problem	29	22
	Maxwellian Distribution of Velocities	30	22
<b>Section VI</b>	<b>Electricity</b>		
	General	31	25
	Action at a Distance	32	25
	Potential Difference	33	27
	Magnetic Effects	34	28
	Problems	35	28
<b>Section VII</b>	<b>Electromagnetic Radiation</b>		
	General	36	28
	Manner of Propagation	37	29
	Waves	38	30
	Wave Picture	39	30
	Definitions	40	31
	Electromagnetic Spectrum	41	32
	Particles or Waves	42	33
	Problems	43	34
<b>CHAPTER 3</b>	<b>GENERAL PHYSICS</b>		
<b>Section I</b>	<b>General</b>	44	36
<b>Section II</b>	<b>Energy and Units</b>		
	Basic	45	36
	The CGS System	46	37
	Force	47	37
	Work	48	38
	Potential Energy	49	38
	Kinetic Energy	50	38
	Mass Energy	51	39
	Electromagnetic Energy	52	39
	Momentum	53	40
	Atomic Mass Units	54	41
	Electric Charge	55	41
	Summary	56	43
<b>Section III</b>	<b>Atomic Structure</b>		
	General	57	43
	History	58	44
	Definitions	59	45
	Avogadro's Law	60	45
	Problems	61	47
	Mendeljeef's Chart	62	47

## **IV**

		<u>Paragraph</u>	<u>Page</u>
<b>Section III</b>	<b>Atomic Structure</b>		
	Rutherford's Atom	63	48
	Bohr's Atom	64	51
	Bohr's Theory Extended	65	56
	Quantum Mechanics	66	58
	How Atoms Are Built	67	59
	Summary	68	62
	Problems	69	62
<b>CHAPTER 4</b>	<b>NUCLEAR PHYSICS</b>		
<b>Section I</b>	<b>Nuclear Structure</b>		
	General	70	63
	Atomic Numbers and Mass		
	Units	71	63
	Isotopes, Isobars, Isomers	72	64
	Nuclear Forces	73	66
	Energy of the Nucleus	74	67
	Nuclear Stability	75	68
	Summary	76	72
	Problems	77	72
<b>Section II</b>	<b>Particles</b>		
	General	78	72
	Description	79	73
	Interaction Between Particles	80	73
	Chart of Elementary Particles	81	74
	Behavior of Particles	82	74
	Wave Particle Dualism	83	78
<b>Section III</b>	<b>Binding Energy</b>		
	General	84	79
	Definition	85	79
	Mass Defect	86	79
	Calculation of Binding Energy	87	80
	Sigma	88	81
	Fission and Fusion	89	82
	Calculation of Energy Release	90	83
	Summary	91	85
	Problems	92	85
<b>CHAPTER 5</b>	<b>RADIATION</b>		
<b>Section I</b>	<b>Radioactivity</b>		
	Introduction	93	86
	History	94	86
	Characteristics of Natural		
	Radioactivity	95	86

		<u>Paragraph</u>	<u>Page</u>
<b>Section I</b>	<b>Radioactivity</b>		
	Alpha Decay	96	89
	Beta Decay	97	91
	Electron Capture	98	94
	Positron Emission	99	94
	Gamma Radioactivity	100	95
	Nuclear Stability and Radioactivity	101	96
	Artificial Radioactivity	102	97
	Decay Laws	103	97
	Radioactive Decay Series	104	101
	Problems	105	108
<b>Section II</b>	<b>Interaction of Radiation With Matter</b>		
	Introduction	106	108
	Ionisation	107	108
	Alpha Particle Interaction	108	109
	Beta Particle Interaction	109	111
	Gamma Ray Interaction	110	114
	Gamma Absorption	111	119
<b>CHAPTER 6</b>	<b>NUCLEAR REACTIONS</b>		
<b>Section I</b>	<b>General Nuclear Reactions</b>		
	Introduction	112	124
	Types of Nuclear Reactions	113	125
	Nomenclature for Nuclear Reactions	114	127
	Rules for Nuclear Reactions	115	128
	Mechanism for Reaction	116	130
	Significance of Q	117	132
	Calculation of Q	118	132
	Probability of the Occurrence of Reactions	119	134
	Cross Section	120	134
	Mean Free Path	121	136
	Resonance Reactions	122	137
	Problems	123	137
<b>Section II</b>	<b>Neutron Reactions</b>		
	Historical	124	137
	Mass of the Neutron	125	138
	Energy Classification of Neutrons	126	138
	Neutron Sources	127	139
	Neutron Induced Reactions	128	140

		<u>Paragraph</u>	<u>Page</u>
<b>Section II</b>	<b>Neutron Reactions</b>		
	Neutron Detectors	129	146
	Problems	130	147
<b>CHAPTER 7</b>	<b>FISSION, FUSION, AND CHAIN REACTION</b>		
<b>Section I</b>	<b>Fission</b>		
	Historical	131	148
	Fission Process	132	149
	Thermal Neutron Fission	133	150
	Inducing Fission	134	150
	Liquid Drop Theory	135	152
	Fission Products	136	153
	Neutrons Emitted	137	154
	Energetics of Fission	138	157
	Probability of Fission	139	158
	Problem	140	159
<b>Section II</b>	<b>Fusion</b>		
	Definition and Source of Energy	141	159
	Reactions	142	159
	Probability of Reaction	143	162
	Fusion and Fission Comparison	144	164
<b>Section III</b>	<b>Chain Reaction and Criticality</b>		
	General	145	165
	Increasing Criticality	146	167
	Quantitative Treatment of Criticality	147	169
	Multiplication	148	173
	Kinetics	149	174
	Summary	150	175
<b>CHAPTER 8</b>	<b>HEALTH PHYSICS</b>		
	Introduction	151	177
	Particles and Their Range	152	177
	The Human Body	153	178
	Cell Composition and Response to Radiation	154	179
	Units	155	180
	Problems	156	183
	Radiation Doses and Effects	157	183
	Internal Radiation Hazards	158	187
	Treatment of Radiation Sickness	159	190

	<u>Paragraph</u>	<u>Page</u>
<b>CHAPTER 8</b>	<b>HEALTH PHYSICS</b>	
	Personal Protective Measures	
	160	190
<b>APPENDIX I</b>	<b>SYMBOLS</b>	193
<b>APPENDIX II</b>	<b>VALUES OF PHYSICAL CONSTANTS</b>	195
<b>APPENDIX III</b>	<b>USEFUL CONVERSIONS</b>	196
<b>APPENDIX IV</b>	<b>TABLE OF ATOMIC MASSES</b>	198
<b>APPENDIX V</b>	<b>GENERAL ELECTRIC CHART OF THE NUCLIDES</b>	200
<b>APPENDIX VI</b>	<b>THE ELEMENTS</b>	202
<b>APPENDIX VII</b>	<b>GLOSSARY</b>	207
<b>APPENDIX VIII</b>	<b>ANSWERS TO PROBLEMS</b>	217
<b>INDEX</b>		

# CHAPTER 1

## MATHEMATICAL PRELIMINARIES

### SECTION I. ALGEBRA

#### 1. GENERAL

In order to study physics, a student needs to recognize that nature has regular laws by which all its various phenomena operate. Many of these laws are familiar; gravity, centrifugal force, action and reaction, and others. The easiest way of describing the regularity of natural phenomena is by means of the language of mathematics. This chapter will review some of the basic concepts of algebra to give enough background for the studies of nuclear physics which follow.

#### 2. THE USE OF SYMBOLS

a. One of the most important basic ideas of algebra is the use of symbols to represent numbers and numerical quantities. Often problems are greatly simplified by using a letter, such as  $x$  or  $y$ , to represent a number which is not known or which may not be specified. For example, it is known that there is a definite ratio between the length of the circumference and the length of a diameter of a circle. The ratio is approximately equal to 3.1416, and is abbreviated by the Greek letter  $\pi$ , which is the symbol  $\pi$ . If a circle has a diameter of 4 cm, it has a circumference of  $4\pi$  cm. The most general way of writing the natural relation between the lengths of diameter and circumference is by means of symbols, rather than by numbers which apply only to a specific case. Thus if the symbol  $d$  represents diameter, then the symbols  $\pi d$  provide a convenient way of writing  $\pi$  times  $d$ , or circumference. If the symbol  $=$  is used to mean equals, or is equal numerically to, then it is possible to write:

$$\begin{aligned}\text{Circumference} &= \pi d \\ \text{or } C &= \pi d.\end{aligned}$$

In algebra, the multiplication sign ( $\times$  or  $\cdot$ ) is often omitted, and multiplication is indicated by placing the two symbolic quantities side by side.

b. The value of use of symbols is seen when two things are considered:

(1)  $C = \pi d$  expresses a very general rule of nature, not only a fact true for certain numerical instances. When it is desired to use this rule, substitute numbers for symbols and solve the equation.

(2) When complicated formulas are needed to describe natural processes, symbols are usually easier to manipulate than the numbers they represent.

### 3. EQUATIONS

a. The quantitative rules of nature are normally best expressed by saying that a certain symbolic representation equals another one. This already has been shown in the relation  $C = \pi d$ , which expresses an equality of two quantities. Such relations are called equations, or formulas.

b. When general rules are expressed as equations, particular cases are usually called solutions. For example, knowing that  $C = \pi d$ , the question might be asked, "What is the circumference of a circle whose diameter is 6 inches?" The solution to this problem is:

$$C = 6\pi \text{ inches.}$$

Or the question might be asked, "What is the diameter of a circle whose circumference is 100 inches?" The solution to this problem is:

$$d = \frac{C}{\pi} = \frac{100}{\pi} \text{ inches.}$$

c. In solving the second problem, use was made of a fundamental law of algebra, one which will be used constantly, that whenever any operation is performed on one side of an equation, the equality is preserved only if the same operation is performed on the other side. This means simply that both sides of the equation  $C = \pi d$  may be divided by the quantity  $\pi$ , and the equation will still be valid.

$$\frac{C}{\pi} = \frac{\pi d}{\pi} = d.$$

This law means that any mathematical operation--multiplication, addition, taking a root--may be performed on an equation and the equality retained, providing exactly the same operation is performed on each side of the equation.

d. As an example of the law, assume that one knows the circumferences of a number of circles and wants to find their areas. Also, it is known that:

$$\text{Area} = \pi r^2, \text{ where } r \text{ is the radius.}$$

If one were to start out with the values of circumference, solve for radius, then find area, much unnecessary arithmetic would be required. This problem may be simplified by keeping the letter symbols:

$$C = \pi d$$

$$\text{and } d = 2r$$

$$\text{Therefore } C = 2\pi r \quad (\text{substitute } 2r \text{ for } d)$$

$$\text{or } r = \frac{C}{2\pi} \quad (\text{divide by } 2\pi)$$

$$\text{Now } A = \pi r^2$$

$$\text{So that } A = \pi \left( \frac{C}{2\pi} \right)^2 = \frac{C^2}{4\pi} \quad (\text{substitute } \frac{C}{2\pi} \text{ for } r)$$

The operations described result in a formula, or equation, expressing area in terms of circumference. The problem then can be solved directly without bothering to find radius  $r$ . In other words,  $r$  was eliminated in the algebraic shuffle. The student should examine each step in the problem above to assure himself that whenever any equation was modified, the same operation of division or multiplication was performed on both sides of the equation, thus maintaining equality. The student should also notice the way in which quantities are substituted in equations; as  $2r$  being substituted for  $d$ , and  $(C/2\pi)$  being substituted for  $r$ .

e. In the course of study here, many equations will be presented, all of which are subject to this same treatment for solution of problems. Try these for practice:

$$(1) E = \frac{3}{2} kT$$

Solve for  $T$  in terms of  $E$  and  $k$ .



$$(2) E = \frac{1}{2} mv^2$$

Solve for  $v$  in terms of  $E$  and  $m$ .

(3) Combine (1) and (2). (Let  $E_{(1)} = E_{(2)}$ ).

(4) Find  $x$  in the equation:  $7x + 5 = 26$ .

(5) Find  $x$  in the equation:  $ax + b = c$ .

#### 4. NEGATIVE NUMBERS

a. Find  $x$  in the equation:  $7x + 8 = 1$ .

##### NOTE

To solve this equation, another concept must be added; that of negative numbers, or numbers less than zero. The idea is not difficult. Imagine a ruler with one end marked "O."

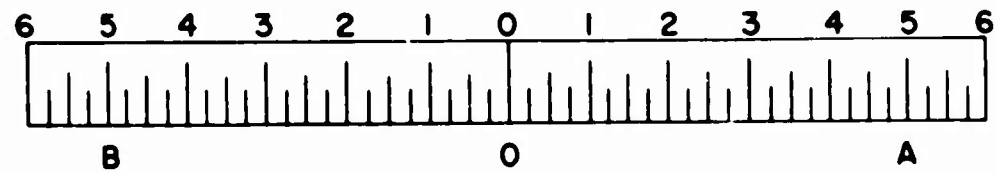


Figure 1. Negative Number Ruler

Point A may be measured at plus 5 inches to the right of O, but for point B, 5 units to the left, it is necessary to place another ruler going in the negative direction. Thus it might be said that B is at -5 units, meaning 5 units on the other side of zero from that side designated positive. In mathematical language, a negative number  $-a$  is defined by the equation:

$$(-a) + (a) = 0.$$

b. Simple rules govern their use, specifically, that multiplication or division of a positive number by a negative number gives a negative number. Multiplication or division of two negative numbers gives a positive number. A positive number subtracted from a smaller positive number gives a negative number. Examples of these rules are:

$$(x)(-y) = -xy$$

$$(-x)(-y) = xy$$

$$3 - 6 = -3$$

To solve the problem in paragraph 4a,  $7x + 8 = 1$ ; subtract 8 from both sides, resulting in  $7x = -7$ ;  $x = -1$ .

## 5. EXPONENTS AND LOGARITHMS

a. Whenever a number is multiplied by itself, as  $a \cdot a$ , a convenient notation has been devised to save writing.  $a \cdot a$  is written  $a^2$ , read "a squared." Similarly,  $a \cdot a \cdot a$  is written  $a^3$ , and read "a cubed," or "a to the third power." When a number such as  $a$  is multiplied by itself  $n$  times, the product may be written  $a^n$  and is read as "a to the  $n$ th power." In this case,  $n$  is called the exponent; and  $a$ , the base of the exponent.

b. This notation has several convenient advantages. For example, the multiplication of  $a \cdot a$  by  $a \cdot a \cdot a$  gives the product  $a \cdot a \cdot a \cdot a \cdot a$ . This problem is more easily written:

$$a^2 \cdot a^3 = a^5.$$

Note that to multiply numbers expressed as powers of the same base, merely add exponents. By the same rule:

$$a^5 \cdot a^3 = a^8, a^{17} \cdot a^3 = a^{20}, \text{ etc.}$$

To multiply  $a^6$  by 1,  $a^6 \cdot 1 = a^6$ , identically. Therefore  $1 = a^0$ . Thus  $a^0 \cdot a^6 = a^6$ , and the rule of adding exponents is valid.

c. Now there must be some number  $x$  for which  $a^3x = 1$ . Following the rules of manipulation,

$$x = \frac{1}{a^3}.$$

Following the rule of adding exponents to multiply, the logical way to write:

$$x = \frac{1}{a^3} \text{ is } x = a^{-3}.$$

Then  $a^{-3} \cdot a^3 = a^0 = 1$ . Thus division is indicated by a negative power.

It is important to realize that the rule is valid only if the powers are to the same base.

d. Work out to the simplest form:

$$(1) (a^3b^2)(a^2b^3).$$

$$(2) \frac{(a^3b^2)}{(a^2b^3)}.$$

$$(3) \frac{(1-x)^3}{(1-x)(1-x^2)}.$$

e. In some cases where numbers are to be multiplied together, it is convenient to reduce them all to powers of the same base and add the exponents. The common base for this purpose is the number 10. For example:

$$100 = 10^2$$

$$1,000 = 10^3$$

$$10,000 = 10^4$$

$$1,000,000 = 10^6$$

To multiply  $100 \times 10,000$ , one can use the table above, and find that the product is:

$$10^2 \cdot 10^4 = 10^{2+4} = 10^6 = 1,000,000.$$

f. Since  $10^0$  equals 1 and  $10^1$  equals 10, it can be deduced that any number between 1 and 10 may be represented as 10 to some power between 0 and 1. In the same way any number between 10 and 100 may be represented as 10 to some power between 1 and 2. In fact any positive number may be represented as 10 to some power. This concept has a very useful application in mathematics.

g. Tables have been made up for all numbers giving the exponent to which 10 must be raised to give each number. The exponents are called logarithms. For instance 2 equals  $10^{0.3010}$ . Therefore, 0.3010 is the logarithm of 2. Ten is called the base.

h. Any number can be used as the base of a system of logarithms. In mathematics the numbers 10 and  $e$  ( $e = 2.71828$ ) are normally used

as bases. A logarithm whose base is 10 is called common logarithm (abbreviated log), one whose base is e is called a natural logarithm (abbreviated ln).

i. From the definition of a logarithm as an exponent, and from the basic laws of exponents, corresponding laws of logarithms may be devised. Use of these laws can save much time in tedious mathematical operations.

j. Law I. The logarithm of the product of two numbers is the sum of the logarithms of the factors. For example:

$$\begin{array}{r} \log 2 = 0.3010 \\ \log 3 = 0.4771 \\ \hline \log 6 = 0.7781 \end{array}$$

Referring to a log table, it is found that the number whose log is 0.7781 is six. What has been done is this:

$$\begin{array}{rcc} 10.3010 & \times & 10.4771 = 10.7781 \\ " & & " \\ 2 & & 3 & & 6 \end{array}$$

k. Law II. The logarithm of a quotient is the logarithm of the dividend minus the logarithm of the divisor. For example,

$$\begin{array}{r} \log 6 = 0.7781 \\ \log 3 = 0.4771 \\ \hline \text{(subtracting)} \quad 0.3010 \end{array}$$

Referring to a log table, it is found that the number whose log is 0.3010 is two.

l. Law III. The logarithm of the rth root of a number is the logarithm of the number divided by r. For example,

$$\log 4 = 0.6020$$

dividing by two gives . . . . 0.3010.

Referring to a log table, it is found that the number whose log is 0.3010 is two.

m. The actual log of a number consists of two parts: an integer called the characteristic, and a decimal part called the mantissa. The mantissa is the part which is found in the log table. The characteristic

is found by applying the rules:

(1) If a number  $N$  is greater than or equal to one, the characteristics of its log is positive and is numerically one less than the number of digits of  $N$  to the left of the decimal point.

(2) If a number  $N$  is less than one, the characteristic of its log is negative and numerically one greater than the number of zeros between the decimal point and the first nonzero figure. For example,

N	Characteristic
1214	3
62	1
8	0
0.01	-2
0.0036	-3

n. The mantissa is found in a table of logarithms. The mantissa of the common log of a positive number is independent of the position of the decimal point. The value of the mantissa depends only on the arrangement of the digits in the number. This can be seen from this table:

$$\begin{aligned}
 5670 &= 5.67 \times 10^3 = 10^{.7536} \times 10^3 = 10^{3.7536} \text{ therefore } \log 5670 = 3.7536 \\
 567 &= 5.67 \times 10^2 = 10^{.7536} \times 10^2 = 10^{2.7536} \text{ therefore } \log 567 = 2.7536 \\
 56.7 &= 5.67 \times 10^1 = 10^{.7536} \times 10^1 = 10^{1.7536} \text{ therefore } \log 56.7 = 1.7536 \\
 5.67 &= 5.67 \times 10^0 = 10^{.7536} \times 10^0 = 10^{0.7536} \text{ therefore } \log 5.67 = 0.7536
 \end{aligned}$$

o. When the number is positive but less than one, it might be expected that the log would be written as a negative number. For example,

$$0.567 = 5.67 \times 10^{-1} = 10^{.7536} \times 10^{-1} = 10^{-0.2464} \text{ or } \log 0.567 = -0.2464$$

p. However in practice, such logs are normally written as a negative characteristic plus a positive mantissa, as  $\log 0.567 = \bar{1}.7536$ , or more commonly  $9.7536 - 10$ . It can be seen that  $9.7536 - 10$  is the same as minus 0.2464. The form  $9.7536 - 10$  is more easily manipulated in problems.

## SECTION II. THE SLIDE RULE

### 6. GENERAL

a. The slide rule is an instrument used to make rapid calculations. It is invaluable to the scientist and the engineer. However, it should be remembered that in slide rule work, accuracy is to some extent sacrificed for speed and that slide rule answers are in most cases only close approximations. These approximations are normally good enough for any but the most exact work.

b. The central sliding part of the rule is called the slide, and the other part the body. The glass runner is called the indicator, and the line on the indicator is the hairline. The marks at the ends of the C and D scales labeled 1 are called indices.

### 7. MULTIPLICATION

Multiplication is performed using the C and D scales.

a. Place either index of the C scale over one of the numbers to be multiplied on the D scale.

b. Place the hairline over the other number on the C scale. Should the number on the C scale not be opposite any number on the D scale, perform step a again, but this time place the other index of the C scale opposite the first number to be multiplied on the D scale. Then proceed to step b.

c. Read the answer under the hairline on the D scale.

d. Since no decimals appear on the scales (2.46, 246, 0.246, etc., are indicated by the same point on the scales), the position of the decimal point must be determined. A rough mental calculation will normally suffice for this.

### 8. DIVISION

Division is also performed on the C and D scales.

a. Place the hairline over the dividend on the D scale.

- b. Set the divisor on the C scale under the hairline.
- c. Read the answer on the D scale under the index of the C scale.

## 9. POWERS

a. One other slide rule operation must be learned. That is the raising of  $e$  to a power.  $e$  is the base of natural logarithms and equals 2.71828. . . . It is useful in many physical processes. For example radioactive decay of certain elements follows the law,

$$N = N_0 e^{-\lambda t}$$

$N_0$  = number of atoms at some time zero.

$N$  = number of atoms left undecayed at some time  $t$ .

$\lambda$  = a constant.

b. A log log slide rule may be used to raise  $e$  to positive and negative powers. To raise  $e$  to a positive power:

(1) Line up the C and D scales so that their indices match.

(2) Place the hairline over the exponent on the C and D scales.

(3) Read the answer under the hairline on the LL1, LL2, or LL3 scale, depending on the value of the exponent. If the exponent is between 0.01 and 0.1, use the LL1 scale; if between 0.1 and 1, use LL2 scale; if between 1 and 10, use the LL3 scale.

c. To raise  $e$  to a negative power,

(1) Line up the C and D scales so that their indices match.

(2) Place the hairline over the exponent on the C and D scales.

(3) Read the answer under the hairline on the LL01, LL02, or LL03 scale, depending on the value of the exponent. If the exponent is between 0.01 and 0.1, use the LL01 scale; if between 0.1 and 1, use the LL02 scale; if between 1 and 10, use the LL03 scale.

## 10. SLIDE RULE PRACTICE PROBLEMS

a.  $27 \times 45$

b.  $313 \times 22.2$

c.  $0.0426 \times 0.379$

d.  $123 \times 0.127$

e.  $1.022 \times 162$

f.  $325 \times 44 \times 0.121$

g.  $\frac{327}{6.21}$

h.  $\frac{6.32}{1.045}$

i.  $\frac{0.032}{4.30}$

j.  $\frac{(9.66) \times (6.81)}{1.24}$

k.  $e^{+4.1}$

l.  $e^{-4.1}$

m.  $e^{-0.12}$

n.  $e^{-.311}$

o.  $e^{-8.88}$

p.  $e^{-.012x} = 0.15$ . Solve for x.



## **CHAPTER 2**

### **BASIC PHYSICS PRELIMINARIES**

#### **SECTION I. GENERAL**

##### **11. INTRODUCTION**

This chapter is intended as a basic physics prerequisite for the course. The whole field of physics is not represented. Only those subjects are included which are required for a basic understanding of later work. These sections should be read with care by those students who have had little or no previous experience with the subjects contained herein.

#### **SECTION II. FORCE, MASS, ACCELERATION**

##### **12. FORCE**

A force is a physical entity which will tend to move a mass. In other words, a force is a push or a pull exerted on some object. This force or push must be described in terms of both magnitude and direction.

##### **13. MASS**

In the above description, the word mass was used, and it should be defined in terms of a force. Mass is that property of a body which resists a change in motion of that body. This means simply that a body which has mass will resist being moved by a force.

##### **14. ACCELERATION**

a. To make the interplay of forces and masses clear, the student needs to know what is meant by a change in motion. Whenever the velocity of a body is changed, it is said to accelerate. (Deceleration is a special case in which the speed decreases.) If the speed changes,

the average acceleration is determined from the formula,

$$\text{average acceleration} = a = \frac{V_2 - V_1}{t}$$

where  $V_2$  is the final speed,  $V_1$  is the initial speed, and  $t$  is the time during which the body accelerates.

b. Now with the concept of acceleration as the rate of change of velocity, a simple single equation can be written which shows how force and mass are related:

$$F = ma.$$

In other words, the force required to accelerate a body is proportional to the mass of the body and to the acceleration produced. Another way of saying this is that the acceleration produced by a force is proportional to the force and inversely proportional to the mass of the body:

$$a = F/m.$$

c. If the velocity is being measured in cm/sec, then the most convenient unit of acceleration is cm/sec per sec. The common scientific unit of mass is the gram. With acceleration measured in centimeters per second per second (cm/sec/sec), then the dimensions of force are:

$$\frac{\text{gm cm}}{\text{sec/sec}} = \frac{\text{gm cm}}{\text{sec}^2}$$

a unit which is called a dyne. Thus a dyne is a unit of force in the metric system cgs units.

## 15. STANDARDS OF MASS

The gram unit of mass is defined as the mass of a cubic centimeter of water at 4° C. From this standard of mass have been made the primary standards of various masses, such as 1 gram and 1 kilogram, which are kept in carefully controlled conditions at the National Bureau of Standards in Washington, D. C., and at other places. To measure a mass, a standard known mass is placed on one side of a balance, and the unknown mass on the other side for comparison.

## 16. WEIGHT

a. If a mass is allowed to fall freely in the gravitational force of the earth, it accelerates at approximately 980 cm/sec<sup>2</sup>. From the

formula,  $F = ma$ , it is seen that the earth's gravity exerts a 980-dyne force on a 1-gram mass. This force is called the weight of the mass in the earth's field. On the moon, the weight of a 1-gram mass is about one-sixth of its earth weight because of the moon's weaker gravitational field. This illustrates the difference between mass and weight. Mass is the inertial property of matter, weight is the force the mass experiences in a gravitational field.

b. Weight is measured by measuring the force exerted by the earth upon an object. This force is the same as the force needed to support the object at rest. Springs may be calibrated in terms of force or weight and used to weigh things. In figure 2, the object weighs four units. It should be noted that this weight measurement is different in principle from the mass measurement of figure 3. In the comparison method, a mass will measure the same on the moon, or any place else, while the calibrated spring weighing method gives a different weight at points with different gravitational accelerations. Often the gram unit is used to indicate a force of 980 dynes. This is not strictly correct, but it is useful. Thus a 1-gram mass, at sea level, is sometimes said to have a "weight" of 1 gram. The student should remember that measuring weight in grams is simply a convention and that it is mass which is correctly measured in grams.

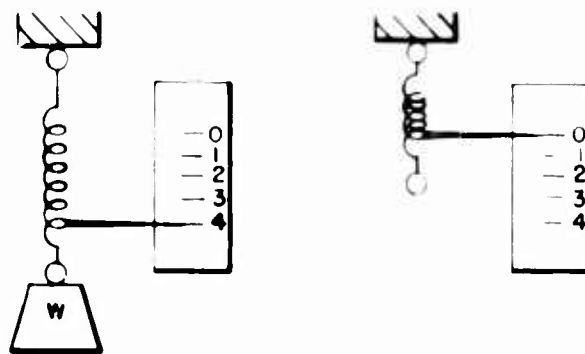


Figure 2. Spring Balance

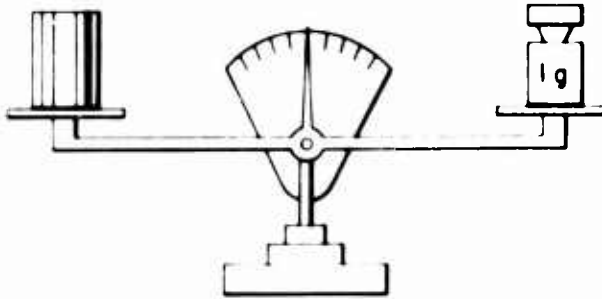


Figure 3. Balance

## 17. MOMENTUM

When an object having mass moves, it is said to possess momentum. Momentum is the quantity of motion of a body and is given by the formula:

$$P = mv.$$

The greater the momentum of a body, the greater the force needed to bring it to rest in a given time.

## 18. PROBLEMS

- a. How much force is exerted by the earth's gravitational field on a 50-gram mass?
- b. If a force of 300,000 dynes is applied to an object whose mass is 210 grams, what acceleration will result?
- c. An object of 60-gram mass increases in velocity from 100 cm/sec to 220 cm/sec in 4 seconds. What average acceleration is produced? What average force is exerted to effect this acceleration?
- d. If an object in the gravity field feels 1,960,000 dynes of force, what is its mass in grams?

### SECTION III. WORK, POWER, ENERGY

#### 19. WORK

a. Work is a physical entity of extreme importance in all scientific thinking. Work is defined as the motion of a force through a distance.

$$\text{Work} = W = F \cdot s$$

The work done on a body is the force exerted on it times the distance through which this force was exerted. Whenever a force is exerted over a distance, work is done.

b. A common metric unit of work is the erg. An erg of work is done if a force of 1 dyne moves through a distance of 1 centimeter. An erg is thus a very small amount of work, by everyday standards. (For everyday physics,  $10^7$  ergs is called a joule.) However, for atomic physics, an erg is an extremely large unit, and smaller units of work are often used. These will be discussed in section II of chapter 3.

#### 20. POWER

a. The rate at which work is done is called power. A given amount of work may be done slowly or rapidly. If done slowly, the power involved is smaller than if it is done rapidly.

$$\text{Power} = \frac{\text{work}}{\text{time}}$$

An everyday unit of power is the watt, which is the power if 1 joule of work is done each second.

$$1 \text{ watt} = \frac{1 \text{ joule}}{\text{sec}} = \frac{10^7 \text{ erg}}{\text{sec}}$$

b. It now should be noted what ergs and watts are in terms of masses, forces, and distances. If an erg of work is done by 1 dyne in 1 centimeter, then:

$$\text{ergs} = \text{dyne} \times \text{cm}$$

$$= \frac{\text{gm cm}}{\text{sec}^2} \times \text{cm} = \frac{\text{gm cm}^2}{\text{sec}^2}$$

These units, expressed in terms of masses, length, and time, are often useful in the solution of problems. See section II of chapter 3.

## 21. ENERGY

a. When work is done on a body by exerting a force and by moving it, then the work is not lost, but is converted to kinetic energy. Energy is the ability of a body to do work, so the moving body may do work on another body. Kinetic energy is energy of motion. Whenever any mass moves, it possesses kinetic energy in the amount:

$$\text{K. E.} = 1/2mv^2,$$

where  $v$  is the velocity of the mass  $m$ .

b. When work is done on a body against a force, such as gravity, which places the body in a position in which the force may act when the body is released, the body possesses potential energy, or energy of position. A common example is the lifting of an object to some height  $h$ . If the mass of the body is  $m$ , the force exerted in lifting it is  $mg$ , and the work done is:

$$W = mgh,$$

where  $g$  is the acceleration due to gravity ( $980 \text{ cm/sec}^2$ ). The potential energy of the body in position  $h$  units above the floor is then,

$$\text{P. E.} = mgh.$$

If the body were dropped, it would be able to do this much work when it struck the floor. The potential energy first would be converted to kinetic energy as the object drops, then this kinetic energy would do work in breaking the object, or heating the floor slightly.

c. The preceding discussion illustrates a fundamental rule about energy--energy may be converted from one form to another, but it is never destroyed or created--the law of conservation of energy. It will be seen later how this classical statement needs reinterpretation for modern atomic physics.

d. Potential energy may be converted to kinetic energy, as in the falling body. As the object drops, the P.E. =  $mgh$  at each instant decreases, since  $h$ , the height from the floor decreases. The body is accelerated with force  $mg$ ; it acquires velocity as it drops; and thus acquires kinetic energy:

$$\frac{mv^2}{2}.$$

The final velocity upon impact is determined by equating the original energy (all of which was potential),  $mgh$ , to the final energy,

$$\frac{1}{2} mv^2$$

all of which is kinetic.

$$mgh = \frac{1}{2} mv^2$$

$$v = \sqrt{2gh}$$

The student should verify that the algebra involved in solving for  $v$  is correct and that the units work out correctly. Remember  $g$  is the acceleration due to gravity.

e. Conversely, kinetic energy may be changed into potential energy, as in the case of a rifle bullet fired into the air. It leaves the gun with a velocity,  $v$ , and essentially zero potential energy. It loses velocity, decelerating due to the force of gravity with an acceleration of  $-g$  until it reaches a height  $h$  where it stops, and all its energy is potential. Then it falls again to earth, until it has lost all potential energy at impact. The height to which the bullet climbs is derived by setting its kinetic energy equal to the maximum potential energy achieved.

$$\frac{1}{2} mv^2 = mgh$$

$$h = \frac{v^2}{2g}$$

Again the student should verify this.

f. Energy may exist in other forms than kinetic and potential. Some of these other forms will be described in this course. Heat energy, it will be shown, is a special kind of kinetic energy; mass

energy and nuclear energies are special kinds of potential energies.

## 22. PROBLEMS

a. How much work is done on a body by a force of 1,000,000 dynes acting through 1 meter? How much kinetic energy does the body possess after this process?

b. How much power is required to do  $10^{16}$  ergs of work in  $2 \times 10^{-5}$  seconds?

## SECTION IV. HEAT ENERGY

### 23. HEAT AND TEMPERATURE

a. Care should be taken to differentiate between heat and temperature. Heat is a measure of energy. As heat is added to a body, some of the energy added manifests itself as kinetic energy of the molecules in the body. Not all the molecules in the system will have the same kinetic energy, but the average kinetic energy per molecule may be considered to be the temperature of the body. Temperature is normally measured by comparison with a body at a known temperature.

b. Suitable bodies at known temperatures are freezing and boiling water. In the commonly used Centigrade scale, freezing water is arbitrarily designated as being at  $0^{\circ}\text{C.}$  and boiling water as being at  $100^{\circ}\text{C.}$  In the Fahrenheit scale,  $32^{\circ}\text{F.}$  corresponds to  $0^{\circ}\text{C.}$  and  $212^{\circ}\text{F.}$  corresponds to  $100^{\circ}\text{C.}$  To convert from one system to the other, the following formula is used:

$$\text{Temperature in } ^{\circ}\text{F.} = \frac{9}{5} (\text{temperature } ^{\circ}\text{C.}) + 32^{\circ}$$

c. If one can imagine a system in which heat has been removed until the molecules have no kinetic energy, one would have a body at the lowest possible temperature or Absolute Zero. This situation should take place at  $-273.18^{\circ}\text{C.}$  Although this temperature has never been reached, it has been selected as zero for another scale called the Kelvin ( $^{\circ}\text{K.}$ ) scale. Since the Kelvin scale uses degrees as basically defined by the Centigrade scale,  $0^{\circ}\text{C.}$  corresponds to  $273.18^{\circ}\text{K.}$  and  $100^{\circ}\text{C.}$  corresponds to  $373.18^{\circ}\text{K.}$  For convenience in those applications where absolute accuracy is not required, absolute zero is generally taken as  $-273^{\circ}\text{C.}$



d. In most scientific work, heat is measured in terms of calories, from which it can be converted into other energy terms (e. g., joules, foot-pounds) if the need arises. A calorie is defined as the heat energy required to raise 1 gram of water 1 degree centigrade.

#### 24. SPECIFIC HEAT

As heat energy is added to a body, the temperature increase is measured, and a quantity called specific heat is calculated. Specific heat is the ratio of heat added to temperature rise occasioned by this energy. Specific heats vary between different substances. The units of heat are chosen so that water has a specific heat of 1 calorie/g  $^{\circ}$  C. In other words, a calorie is the heat energy required to raise 1 gram of water 1 degree centigrade. From other experiments involving the generation of heat by mechanical means, it is known that one joule ( $10^7$  ergs) of energy is equivalent to 0.24 calories. This equivalence of mechanical work and heat energy was a decisive refutation of the old heat-fluid theory.

#### 25. THERMAL EXPANSION

Many substances change their physical dimensions when their temperature is changed. Most metals expand slightly with increase in temperature and contract with decrease. The same is true for fluids, except the expansion is relatively greater; this effect is used in many thermometers to measure temperature.

### SECTION V. KINETIC THEORY

#### 26. MOLECULAR MOTION

a. The various heat phenomena are all explainable from one basic assumption. This assumption has had undeniable experimental verification since about 1900. All matter is composed of small building blocks, which are particles called molecules. These molecules are much too small to be seen even with the most powerful optical microscopes, but the effects of their behavior may be measured. Molecules are in continuous random motion, bouncing around and colliding with each other. The basic assumption is that this random motion of molecules is responsible for the thermal behavior of gases. The internal structure of the molecules is also partly responsible for the behavior of matter at extremely high or low temperatures.

b. As early as the 1820's, a botanist named Brown had noticed with a microscope that pollen grains suspended in water were in constant agitation with apparently random motions. This phenomenon became known as Brownian movement. In 1908, the French scientist, Perrin, prepared particles smaller than pollen grains, and of definitely known sizes and masses, and suspended them in various liquids. He found that the Brownian movement really was random, and that the vigor of this motion depended strikingly upon the temperature of the liquid, the type of liquid used to suspend the colloidal particles, and the mass of the particles. The results fit perfectly with the theory that these visible particles are being bombarded and moved continuously by invisible molecules of the liquid. Thus, a fairly direct proof of the existence of molecules is available by which measurement may be made of their masses and other properties. More modern experiments confirm these results in other ways.

## 27. DEFINITIONS

a. A molecule is the smallest particle of a substance which retains the normal chemical properties of that substance. Molecules are composed of one or more particles called atoms. An atom is the smallest particle of an element which retains the chemical properties of that element. An element is a substance which cannot be separated into substances different from itself by ordinary chemical means.

b. To illustrate these definitions, consider a molecule of water, ( $H_2O$ ). The molecule is composed of 2 hydrogen atoms and 1 oxygen atom, bound together as a unit with the chemical properties of water. The hydrogen atoms or the oxygen atom, if split apart from the molecule, have the chemical properties of the elements hydrogen and oxygen, respectively. Neither hydrogen nor oxygen atoms can be broken down by chemical means to form substances with other chemical properties; hence they are elements. Further examples of elements are copper, iron, tin, nitrogen, and uranium. It is seen that the molecules of many elements, iron for example, are the same as the atoms of that element. For many elemental gases, this is not so. In these gases, two similar atoms pair up to form a molecule.

## 28. KINETIC THEORY

a. In using the assumption of kinetic theory to explain thermal behavior of gases, the student normally will be unconcerned with the detailed internal structure of the molecules. He will only need to remember that these molecules are moving about in a completely random way. The principal result of the theory is the understanding that heat energy is the energy of random motion of the molecules.

b. Although individual instantaneous motion of a molecule is random, the average velocity of a molecule over a period of time, or the average instantaneous velocity of a large number of molecules, is not random. The temperature of a gas depends directly upon the average energy of the molecular motions. If heat energy is added to a gas, the molecules speed up somewhat, their average energy is increased, and the temperature is increased.

c. The average kinetic energy of a single molecule is:

$$\frac{1}{2} m \bar{v}^2,$$

where  $\bar{v}$  is the average velocity of the molecule and  $m$  is its mass. The total energy of a gas containing  $N$  molecules is thus:

$$\frac{N}{2} m \bar{v}^2.$$

The absolute temperature  $T$  for a monatomic gas may be obtained from the equation:

$$\frac{3}{2} kT = \frac{1}{2} m \bar{v}^2$$

$k$  is called Boltzmann's constant, where:

$$k = 1.38 \times 10^{-16} \text{ erg/}^\circ\text{K. / molecule.}$$

It is seen at once that absolute zero is the temperature at which all molecular motion ceases. This equation results from assuming that the molecular energy determines the temperature.

## 29. PROBLEM

Use  $\frac{3}{2} kT = \frac{1}{2} m \bar{v}^2$  to calculate the average velocity of a hydrogen molecule  $H_2$  in a gas at  $20^\circ\text{C}$ . The mass of a hydrogen atom is  $1.6 \times 10^{-24}$  grams.

## 30. THE MAXWELLIAN DISTRIBUTION OF VELOCITIES

a. Consider a gas at a certain temperature, for example, oxygen, enclosed in a 1 cubic centimeter box at a temperature  $T_1$ . All of the molecules of oxygen will be in motion, and they will be moving in all different directions and at varying rates of speed; that is, they will all have different velocities. In this discussion, the word

velocity will be taken to mean the magnitude of the velocity without regard to the direction of motion of the molecules.

b The velocity of the molecules will vary over a very great range. Some molecules will travel very slowly while a few will travel very fast. For the specific temperature  $T_1$ , there will be some velocity  $v_p$  which is most probable, known as the most probable velocity.

c. If the temperature is now raised to a new temperature  $T_2$ , the average velocity of the molecules is also raised because an increase in temperature is an indication of increased kinetic energy and hence increased velocity. When the temperature is raised, more molecules will travel at the higher velocities and fewer molecules at the lower velocities. It is possible to represent this variation in velocities for a particular temperature by means of a curve such as is shown in figure 4. This curve is known as the Maxwellian distribution of velocities. In this distribution, the total number of oxygen molecules is represented by the area under the curve. The shaded area under the curve represents the number of molecules with energies greater than  $v_1$  but less than some higher velocity  $v_2$ .

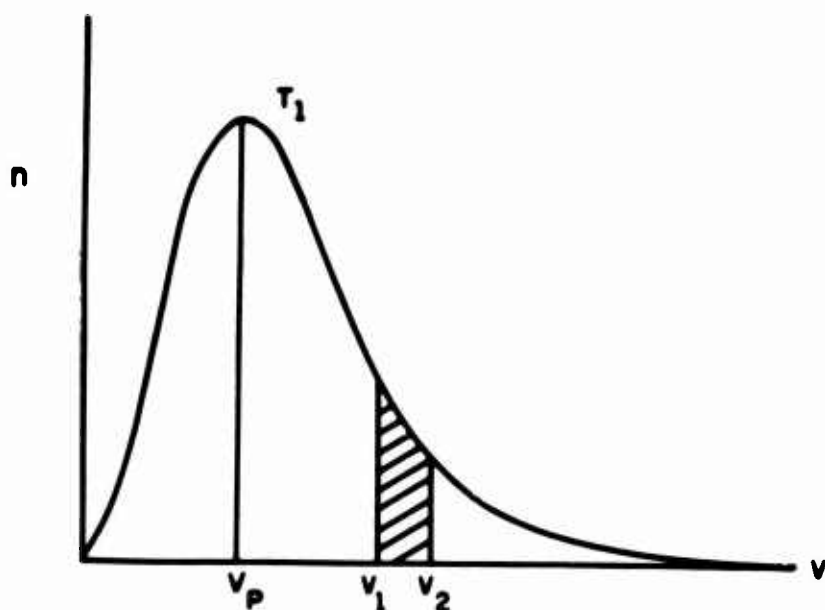


Figure 4. Maxwellian Distribution of Velocities for Temperature  $T_1$

The effect of increasing the temperature to  $T_2$  is shown in figure 5. Here the curve for the lower temperature  $T_1$  has been included for comparison. The total area under both curves will remain the same because the total number of molecules is unchanged. The areas under the curve at higher velocities, such as between  $v_1$  and  $v_2$ , have increased indicating that more molecules are traveling at these higher velocities.

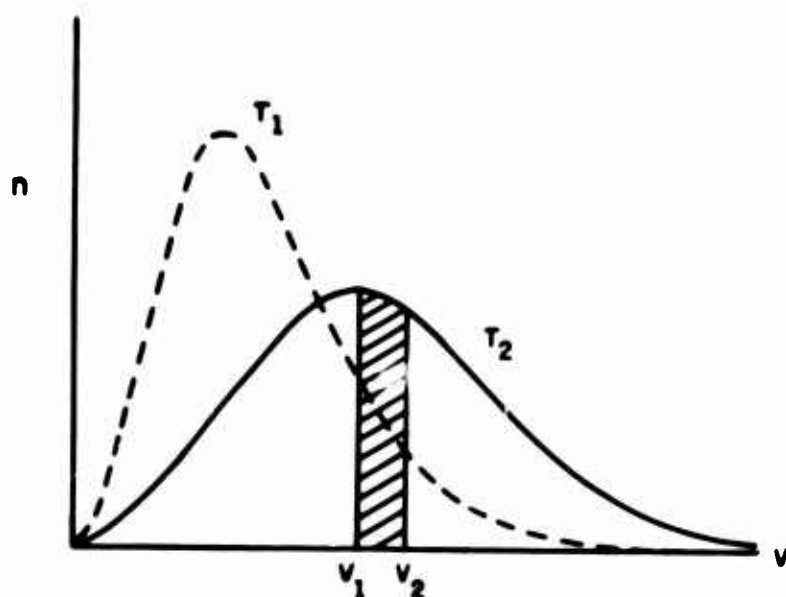


Figure 5. Maxwellian Distribution of Velocities for Temperatures  $T_1$  and  $T_2$  ( $T_2 > T_1$ )

d. The fact that there is a distribution of velocities and that this distribution changes at higher temperatures is of considerable importance later in this course.

## SECTION VI. ELECTRICITY

### 31. GENERAL

a. This section will not be concerned with electric circuits, but with a few basic principles of electrostatics and the behavior of electric charges.

b. In every atom of any material, there are two types of electricity which are called positive and negative charges. From experiments involving the passage of electricity through gases, it has been learned that the negative electric charge is quite mobile and is essentially responsible for the phenomenon of electric conduction. These negative charges are called electrons.

c. Whenever a body becomes electrically charged, it has either gained an excess of electrons or has lost some of its electrons, leaving the residual net charge negative or positive, respectively. Bodies may be charged with electricity in various ways, a common one being the frictional rubbing off or on of electrons.

### 32. ACTION AT A DISTANCE

a. The most significant fact about electric charges is that they exert forces on each other, even though the charges are not touching. This action at a distance is a general property of many types of forces in physics, such as gravity, electricity, and magnetism. In the case of electric charges, the force exerted depends on the sizes of the charges and the distance  $r$  between them:

$$F \propto \frac{q_1 q_2}{r^2}$$

where  $q_1, q_2$  are the charges, the  $\propto$  sign means is proportional to. The units of charge must be defined before this proportion can be made into an algebraic equation.

b. A common scientific unit of charge is the electrostatic unit (esu) of charge. This unit is defined as that amount of charge which will exert a force of 1 dyne on an identical charge placed 1 centimeter away. By careful measurements, it has been found that an electron has a charge of:

$$-4.8 \times 10^{-10} \text{ esu.}$$

The minus sign indicates that an electron is the negative type of electricity.

Now if we measure charges  $q_1$  and  $q_2$  in esu and the distance between them in centimeters, the force  $F$  in dynes is:

$$F = \frac{q_1 q_2}{r^2}.$$

This force will be attractive, positive, if the charges are of opposite sign; and repulsive, negative, if the charges are alike.

c. Picking up bits of paper with a charged comb illustrates these electrostatic forces. By combing the hair rapidly, an excess of electrons may be rubbed onto the comb, leaving it with a net residual negative charge. As the comb is placed near the paper bits, the negative charges on the comb exert forces on the electrons in the paper, repelling some of them toward the far side of the paper. See figure 6.

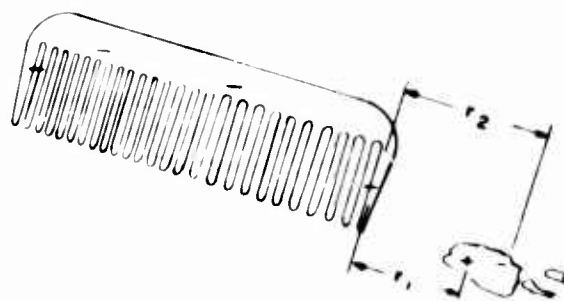


Figure 6. Electrified Comb

The paper then has a slight positive excess on the side next to the comb, and a slight negative excess on the side away from the comb. The distance between the comb and the positive charge is less than that between the comb and the negative. Therefore, the net force exerted on the paper will be an attractive force.

$$\text{Attractive force } F_1 = \frac{q_{\text{comb}} q_{\text{paper}} (+)}{r_1^2}.$$

$$\text{Repulsive force } F_2 = \frac{q_{\text{comb}} q_{\text{paper}} (-)}{r_2^2}.$$

Net force =  $F_1 - F_2$ , attractive, since  $r_2$

is slightly larger than  $r_1$ .

### 33. POTENTIAL DIFFERENCE

a. The student should notice now that a charge possesses potential energy when it has a force exerted on it by another charge. In other words, it can do work by virtue of its position. Or, conversely, work must be done to move it against the electric force. For example, consider a positive and a negative charge. They will move toward each other. If one charge is held in a fixed position, a force must be exerted on the other to move it away from the fixed charge and work is done. The potential energy of a charge at some point in the electric field of another is defined as the work that would be done in moving that charge from infinity to its present position. According to Coulomb's law:

$$\text{P. E.} = \frac{q_1 q_2}{r}$$

where  $r$  is the distance between the two charges. This energy of interaction of two charges will be important for our later discussion of atomic structure.

b. It is often convenient to think of the work that can be done by an electric field in terms of potential difference. The unit of potential difference is the volt. It is possible to think of voltage as a sort of electrical pressure which pushes charges around. The electrostatic unit system has a unit of potential difference called the stat volt, or e. s. volt; which is a large unit for practical everyday electrical work. The practical volt is 1/300 esv.

c. An esv is that amount of potential difference through which one erg of work is done in moving an esu of charge. Potential difference is a unit of energy difference per charge unit; it is a specific potential energy change. To illustrate the use of this definition, calculate the energy gained by an electron passing through 1-volt potential difference:



$$\left( \frac{1}{300} \text{ esv} \right) (4.8 \times 10^{-10} \text{ esu}) = 1.6 \times 10^{-12} \text{ ergs.}$$

#### 34. MAGNETIC EFFECTS

Whenever a charge moves through space, an electric current is said to flow, and some kind of a magnetic field is set up. Magnetic fields exert forces on other magnetic fields, such as those generated by other currents or by permanent magnets. It is not necessary to be very concerned here about the details of magnetic forces, except to note that a changing or moving magnetic field will induce or set up an electric field. This complementary fact to the first sentence in this paragraph was discovered in the last part of the 19th century and is important to our understanding of generators and of electromagnetic waves, such as radio and light.

#### 35. PROBLEMS

The following problems summarize the salient points of this section:

- a. Calculate the energy in ergs acquired by an electron falling through a potential difference of 1 million volts.
- b. What force is exerted between 2 unlike charges of 1 electronic charge each, separated  $10^{-8}$  cm? What is the potential energy of one in the field of the other?
- c. What force is exerted between 2 like charges of 1 electronic charge each, separated  $10^{-12}$  cm? What is the potential energy of one in the field of the other?

### SECTION VII. ELECTROMAGNETIC RADIATION

#### 36. GENERAL

a. Since this unclassified course material is largely concerned with radiation, a few of the concepts of electromagnetic waves will be introduced here as a preliminary background for later study.

b. All radiation may be considered as a method of transmission of energy. By various means, a molecule, atom, or some part of an atom, may give up some of its energy into a form of radiation. This

radiation may travel to some other point of space and then be absorbed by another molecule, atom, or part of an atom. The energy of the radiation is thus added to that of the absorbing matter.

### 37. MANNER OF PROPAGATION

a. The electromagnetic type of radiation will be discussed. Because of the fact mentioned in paragraph 34 that a varying magnetic field induces an electric field, and the complementary principle that a changing electric field sets up a magnetic field, it is possible to gain a fairly basic understanding of how electromagnetic waves are propagated. Radio waves are an example of electromagnetic waves. A rapidly varying electric current is established in a radio antenna by the transmitter. This current sets up a changing magnetic field in the vicinity of the antenna, which in turn induces a changing electric field. The electric field and the magnetic field then alternately establish one another as they move out from the antenna. This process is illustrated in figure 7. Since electric field lines have both magnitude and direction, they are shown as vectors along a certain line of propagation from the antenna. Notice that the electric and magnetic fields alternately are strong and weak, and that they reverse in direction in a regular way. A complete cycle of the wave is shown by figure 7.



Figure 7. Electromagnetic Waves

b. What is actually happening in the electromagnetic wave is that the electric and magnetic fields propagate, or move along in space, by a mutual interaction. The way in which the fields move is determined by the manner in which one field generates the other. For empty space, an electromagnetic wave moves along with a velocity

equal to:

$$2.9976 \times 10^{10} \text{ cm/sec, or } 3 \times 10^{10} \text{ cm/sec,}$$

a value usually abbreviated  $c$ , or the speed of light. In other materials, such as glass or water, the velocity of propagation is smaller because of the dielectric properties of these materials. In other words, the way in which the electric field is set up is slightly different in glass than in air or vacuum. This difference in velocity is accounted for in the index of refraction of glass and is the principle of operation of a lens. In this course we are concerned only with the velocity of light in a vacuum. This value seems to be a universal constant of nature.

### 38. WAVES

a. A wave is any propagated periodic disturbance in a transmission medium. In the case of electromagnetic waves, the disturbance which is propagated is the electric and magnetic field, and they disturb the normal no field condition of empty space in a regular way. Notice from figure 7 that the direction in which propagation occurs is perpendicular to the disturbance being propagated. This fact is true of all transverse waves.

b. A water wave is another example of a transverse wave; the disturbance of the water moves up and down, the wave itself moves horizontally. As an example of a nontransverse wave, consider a long coiled spring, which is given periodic taps at one end. The disturbance in this case is a compression or extension of the spring, parallel to the direction of propagation. This type of wave, of which sound waves are the most common example, is called longitudinal. This course will be mostly concerned with transverse waves, since electromagnetic waves are of this type.

### 39. WAVE PICTURE

If it were possible to take an instantaneous picture of the electric field vectors in an electromagnetic wave, the picture might look like figure 8. The arrows represent the direction of the field; and the height of the curve, the magnitude. Notice the regular way in which the field varies. If one measured the variation of the field at a single point, he would find that it varied as a function of time, passing through regular peaks and valleys. To see this, imagine yourself at a point  $P$  on the axis, and let the wave move by you. The wave is positive, then negative, then positive again, in the same regular way. This periodicity in both space and time characterizes all wave propagation.

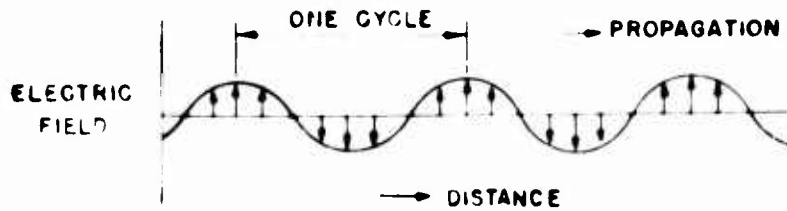


Figure 8. Wave Picture

#### 40. DEFINITIONS

a. A few basic definitions should be learned. The distance between corresponding adjacent points on a wave is called a wavelength, abbreviated by the Greek letter lambda,  $\lambda$ . A cycle is the complete wave between two corresponding points. Thus a wavelength is the distance in which a cycle is accomplished. The number of cycles which pass a given point in a second is called the frequency of the wave, abbreviated  $\nu$  (nu).

b. For a wave of wavelength  $\lambda$  traveling at a velocity  $c$ , it will be seen that the number of cycles which pass a fixed point in a second is  $c/\lambda$ , thus:

$$\nu = \frac{c}{\lambda}.$$

Conversely, if a number  $\nu$  cycles per second are observed, and each one is  $\lambda$  long, then the speed with which they pass is  $\lambda\nu$ . Thus  $\lambda\nu = c$ . The student should attempt this reasoning for deriving this formula in the form:

$$c/\nu = \lambda.$$

This relation between frequency, wavelength, and velocity of propagation is a general formula holding for all types of wave propagation.

c. Example problems:

- (1) What is the wavelength of a radio wave whose frequency is 1000 kc/sec?

(1 kc = 1000 cycles)

$$\lambda = \frac{c}{\nu} = \frac{3 \times 10^{10} \text{ cm/sec}}{1,000,000 \text{ cycles/sec}} = 3 \times 10^4 \text{ cm}$$
$$= 300 \text{ meters.}$$

(2) A velocity of light determination is made from a frequency and wavelength measurement.

$$\nu = 6.700 \times 10^8 \text{ cycles/sec.}$$

$$\lambda = 44.70 \text{ cm.}$$

What is c?

$$\nu\lambda = 2.99 \times 10^{10} \text{ cm/sec.}$$

d. The time for one cycle is called the period of the wave. Thus the period T is the reciprocal frequency,

$$T = \frac{1}{\nu}.$$

For example, the period of a 1-megacycle frequency wave is 1 microsecond.

e. Wave number is a useful term for dealing with light waves. The wave number, abbreviated  $\bar{\nu}$ , or n, is defined as the reciprocal wavelength,

$$\bar{\nu} = \frac{1}{\lambda}.$$

and therefore has units of  $\text{cm}^{-1}$ .

Another mathematical definition is  $\bar{\nu} = \nu/c$ , or frequency divided by velocity. The wave number of light whose  $\lambda = 4 \times 10^{-5} \text{ cm}$  is:

$$\bar{\nu} = \frac{1}{\lambda} = \frac{1}{4} \times 10^5 = 25,000 \text{ cm}^{-1}. \text{ (Violet light.)}$$

f. The angstrom unit,  $\text{\AA}$ , is a useful unit for measuring light wavelengths. It is defined as  $10^{-8} \text{ cm}$ , so that red light, with  $\lambda = 8 \times 10^{-5} \text{ cm}$ , has  $\lambda = 8000 \text{ \AA}$ .

#### 41. ELECTROMAGNETIC SPECTRUM

a. It has been noted already that radio waves are electromagnetic. They are waves whose wavelengths range from 20,000 meters to a few centimeters. Infrared rays are electromagnetic waves whose

wavelengths range from a few millimeters to about  $10^{-4}$  centimeters. Light rays, visible to the human eye, range in wavelength from  $8 \times 10^{-5}$  to  $4 \times 10^{-5}$  cm. Ultraviolet rays are of shorter wavelength, and X-rays are still shorter. A range of wavelength values such as has been described is called a spectrum. The electromagnetic spectrum is summarized in figure 9.

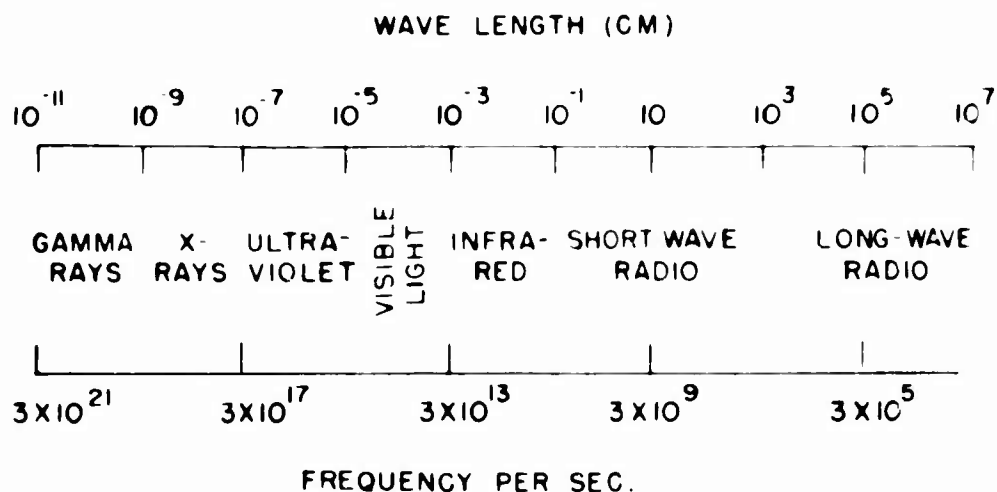


Figure 9. Electromagnetic Spectrum

b. These various types of electromagnetic radiation have all the characteristics and properties of electromagnetic waves; frequency, wavelength, velocity =  $c$ ; and they are all composed of electric and magnetic field variations. However, they may originate in various ways. The longer radio waves are usually generated directly by radio transmitters. The infrared waves are generated by somewhat excited or hot molecules. Heat radiation is infrared. Visible and ultraviolet light are produced by excited atoms by processes to be described later. X-rays are generated in several ways, either by rapid deceleration of charged particles, or by extreme excitation of the atoms in matter. Gamma rays are generally produced in the nuclei of atoms.

## 42. PARTICLES OR WAVES

a. In experiments with light, ultraviolet and X-rays, physicists have found that there are two types of explanations for the observed phenomena. In many experiments, light rays behave as though they were waves, as described here so far. Interference, diffraction, and

polarization experiments are most plausibly explained in terms of electromagnetic waves; that is, light appears to be a long train of waves.

b. In other experiments, however, light rays behave as though they were small particles, bundles of energy, traveling at the velocity  $c$ . In a photoelectric effect experiment, and in many experiments with shorter wavelengths, X-rays and gamma rays, the rays appear to be composed of packets of energy called photons. A photon may be absorbed all at once or impart its energy in sudden discrete amounts.

c. The question is often raised as to whether light is composed of photons or waves, since the concepts seem so different. The answer is that light is emitted and absorbed as photons, but travels as though it were a long continuous wave. Light apparently is some kind of phenomenon, not wholly particle-like nor wholly wavelike, but something which may act like either particles or waves in experiments. While this answer may seem intellectually unsatisfying, the student should be comforted to know that it is both unsatisfying and stimulating to experimental and theoretical physicists who are doing research on the fundamental nature of light.

d. The energy of a photon associated with an electromagnetic wave of frequency  $\nu$  can be shown to be:

$$E = h\nu$$

where  $h$  is a known constant number,  $h = 6.6 \times 10^{-27}$  erg sec, called Planck's constant. Planck was one of the first physicists to recognize the existence of photons. This concept of photons, and of the energy carried by them, is important principally for the higher frequency, higher energy end of the electromagnetic spectrum.

#### 43. PROBLEMS

a. What is the frequency of a wave whose velocity is 10 meters per second, and whose wavelength is 0.1 meter?

b. What is the wavelength of a station whose frequency is 1500 kc, at the upper end of the broadcast band? What wavelength for a radar frequency of 15,000 Mc?

c. What is the energy of a photon of 15,000 Mc radiant energy? Compare this energy with that of a photon of light energy of  $6 \times 10^{-5}$  cm. wavelength.

d. What is the wavelength of radiation whose frequency is  $1.5 \times 10^{15} \text{ sec}^{-1}$ ? In what part of the spectrum does it lie?

e. What is the frequency of a photon whose energy is 1-electron volt ( $1.6 \times 10^{-12} \text{ ergs}$ )? What wavelength? What part of the spectrum?

f. How much energy is associated with a ray of wavelength 0.01 Å? What frequency? What part of the spectrum?



## **CHAPTER 3**

### **GENERAL PHYSICS**

#### **SECTION I. GENERAL**

44. This chapter is composed principally of the actual material presented and required of students in the course. Lecture data and other supplementary information have been added to a bare outline of actual lesson plans. Since this chapter is intended to collate and organize the material into a single unit for study, all the necessary unclassified physics for the course has been included.

#### **SECTION II. ENERGY AND UNITS**

##### **45. BASIC**

a. In this section are summarized the basic concepts of energy, which ideas already have been expressed in more detail in paragraph 21. They are mentioned here again briefly for the sake of completeness. Also, there is a summary of units useful in this course and in the work for which this course prepares the student.

b. Units are the means of labeling physical quantities. Every physical quantity may be measured and expressed in terms of some units. For example, a distance may be measured as a number of centimeter units. This text will use principally the metric system of units because of its convenience.

c. Three basic dimensions should be noticed: mass (M), length (L), and time (T). It will be found that units for every physical quantity may be expressed in terms of these three dimensions. For example, velocity units are length per time,  $L/T$ ; acceleration units are

velocity per time, or

$$\frac{L/T}{T},$$

which may be written conveniently  $L/T^2$ .

#### 46. THE CGS SYSTEM

The system of units used here is the cgs, centimeter-gram-second system, where length is measured in centimeters, mass in grams, and time in seconds. A centimeter is a length based on the distance from the north pole to the equator at a certain longitude. The primary standard meter is kept at the National Bureau of Standards. A gram is defined as the mass of a cubic centimeter of water at  $4^{\circ}\text{C}$ . A primary standard gram mass is also kept at the National Bureau of Standards, from which secondary standards may be calibrated for laboratory use in other places. A second is defined as one 86,400th part of a mean solar day. Recently, this time unit has been redefined in terms of certain colors of light, for easier laboratory calibration. Therefore, it will be seen that the units for measuring physical quantities are well defined and meaningful.

#### 47. FORCE

a. Now the question arises, "What are the units of other physical quantities, as for example, forces and energies?" In order to discuss these units, these physical entities will be defined quantitatively. Remembering Newton's law of motion,

$$F = ma.$$

The cgs unit of mass is the gram; the unit of acceleration is the  $\text{cm/sec/sec}$ , or  $\text{cm/sec}^2$ . Therefore, the most convenient unit of force will be  $\text{gm cm/sec}^2$ , the amount of force which will accelerate a 1-gram mass at 1 centimeter per second per second. This cgs unit of force is called a dyne. One should notice that the dimensions of force are:

$$\frac{ML}{T^2}.$$

b. The force which gravity exerts on a body of mass  $m$ , i. e., its weight, is thus equal to  $mg$ , where  $g$  is the gravitational acceleration. This distinction between weight and mass should be perfectly clear to the student. Weight is the force which acts upon a mass due to the

gravitational field; it is the force which causes a mass to accelerate to the earth with an acceleration  $g$ . At sea level,  $g = 980 \text{ cm/sec}^2$ . Mass is the inertial property of matter by which it resists a change in its state of motion, and therefore mass is independent of gravity.

#### 48. WORK

Remembering that work is done when a force is moved through a distance, a convenient cgs unit for work may be found. Since energy is the ability to do work, energy should have the same units.

$$\begin{aligned}\text{Work} &= (\text{force}) (\text{distance}) \\ &= \text{dyne} \cdot \text{cm} \\ &= \frac{\text{gm cm}}{\text{sec}^2} \cdot \text{cm} = \frac{\text{gm cm}^2}{\text{sec}^2} \\ &= \text{ergs}\end{aligned}$$

The cgs unit of work or energy is called an erg. It is the work done when 1-dyne force acts through a distance of 1 centimeter. The dimensions of work are  $ML^2/T^2$ .

#### 49. POTENTIAL ENERGY

Potential energy,  $mgh$ , of a mass,  $m$ , at a height,  $h$ , above a reference level is also measured in ergs in cgs system, as can be shown by multiplying the units in the equation below.

$$\begin{aligned}mgh &= (\text{grams}) \left( \frac{\text{cm}}{\text{sec}^2} \right) \text{cm} \\ &= \text{gcm}^2/\text{sec}^2 \\ &= \text{ergs}\end{aligned}$$

The amount of ergs is the work that can be done when this potential energy is released. In accordance with the law of conservation of energy, potential energy is convertible to kinetic energy, or energy of motion.

#### 50. KINETIC ENERGY

Kinetic energy,  $\frac{1}{2}mv^2$ , also has work units, since

$$\text{gm} \left( \frac{\text{cm}}{\text{sec}} \right)^2 = \frac{\text{gm cm}^2}{\text{sec}^2} = \text{ergs.}$$

## 51. MASS ENERGY

In the early 20th century, Einstein proposed that the law of conservation of energy be modified to include another type of energy, called mass energy. It has been found that mass in some cases may be converted into other forms of energy according to the formula:

$$E = mc^2$$

where  $m$  is the mass which converts, and  $c$  is the velocity of light,  $3 \times 10^{10}$  cm/sec. The student should verify that  $E$  is given in ergs when  $m$  is given in grams. The newer law states that the total sum of mass and energy is never destroyed or created, but only converted from one form of energy or mass to another.

## 52. ELECTROMAGNETIC ENERGY

Since energy is transmitted by radiation, it is necessary to consider the electromagnetic form of energy. Light and other electromagnetic radiations travel like wave phenomena obeying the usual wave equations, such as

$$c = \lambda \nu$$

where  $\lambda$  is wavelength,  $\nu$  is frequency, and  $c$  is the velocity of light. However, light is emitted and absorbed only in discrete quantities, and these packets of light energy are called photons, or light quanta. For an electromagnetic radiation of frequency  $\nu$ , the energy of the photon is

$$E = h\nu = \frac{hc}{\lambda}$$

$h$  is Planck's constant,  $6.6 \times 10^{-27}$  erg seconds;  $\nu$  is expressed in cycles per second; i. e.,  $\text{sec}^{-1}$ ; and  $E$  is given in ergs. (The dimensions of the unit cycles per second is  $1/T$ , since a cycle is a dimensionless unit.) This quantum equation means that if an energy,  $E$  ergs, is to be released in the form of radiation, it will be emitted as

a photon; and when the wavelength of the light is measured, it will be

$$\lambda = \frac{hc}{E}.$$

The most convenient description is given in terms of wave number  $\bar{\nu}$ .

$$\bar{\nu} = \frac{1}{\lambda} = \frac{E}{hc}$$

When light interacts with matter, it acts as if it were composed of particles having definite energy. These particles have momentum, given by

$$p = \frac{E}{c} = \frac{h\nu}{c} = \frac{h}{\lambda},$$

and apparent mass, given by

$$m = \frac{h}{c\lambda}.$$

Actually the rest mass of a photon must be zero, but in their absorption in matter, they often act as though they had a mass which depends on their wavelength. These quantum considerations are especially true for the higher frequency, higher energy radiations, such as visible light, ultraviolet, X-rays, and gamma rays.

### 53. MOMENTUM

Another physical entity whose units should be mentioned is momentum, the quantity of motion of a moving body:

$$p = mv$$

where  $p$  is momentum,  $m$  mass, velocity  $v$ . In the cgs system,  $p$  has units gm cm/sec. Related to this concept is angular momentum, which is possessed by a body moving around a reference point. If  $r$  is the radius from the body to the reference axis (the center of its circular orbit) and  $p$  is its linear momentum, then angular momentum  $L = pr = mvr$ .

The units of angular momentum are thus:

$$\frac{\text{gm cm}^2}{\text{sec}}$$

in the cgs system, which are the same as the units erg-sec, having dimensions

$$\frac{ML^2}{T}$$

#### 54. ATOMIC MASS UNITS

When dealing with atoms, the extremely small sizes and masses cause some inconvenience in description by the cgs unit system. The mass of an atom is usually expressed in atomic mass units, or amu. One amu is defined as 1/16 the mass of the oxygen-16 atom. The mass in grams corresponding to one atomic unit is  $1.66 \times 10^{-24}$  grams.

#### 55. ELECTRIC CHARGE

a. The most convenient unit of electric charge in dealing with atomic systems is the electronic charge unit, e. This charge is equal to  $4.8 \times 10^{-10}$  electrostatic units of charge. (One esu is that amount of electric charge which when placed 1 centimeter from an identical charge in a vacuum will experience an electric force of 1 dyne.)

b. The most convenient and most used unit of energy in atomic and nuclear systems is the electron volt, abbreviated ev. One ev is the energy which an electron will pick up in accelerating through an electric field of 1-volt potential difference. Since the electronic charge e is  $4.8 \times 10^{-10}$  esu, and there are 300 practical volts in an electrostatic voltage unit, then the following relation between ergs and ev can be derived:

$$\begin{aligned} 1 \text{ ev} &= \frac{(4.8 \times 10^{-10} \text{ esu}) (1 \text{ esv})}{300 \frac{\text{esv} \times \text{esu}}{\text{erg}}} \\ &= 1.6 \times 10^{-12} \text{ erg.} \end{aligned}$$

The unit, Mev = million electron volts, is also used. Since

$$1 \text{ Mev} = 1.6 \times 10^{-6} \text{ erg,}$$

one amu converted to energy by  $E = mc^2$  corresponds to:

$$\frac{(1.66 \times 10^{-24} \text{ gm}) (3 \times 10^{10} \text{ cm/sec})^2}{1.6 \times 10^{-6} \text{ erg/Mev}} = 931 \text{ Mev.}$$

Units Summary			
Quantity	Symbol or Formula	Dimensions	CGS Units
Mass	M, m	M	gm
Length	L, s, d	L	cm
Time	T, t	T	sec
Velocity	v	L/T	cm/sec
Acceleration	$a = \frac{v_{av}}{t}$	L/T <sup>2</sup>	cm/sec/sec
Acceleration of Gravity	g	L/T <sup>2</sup>	980 cm/sec <sup>2</sup>
Weight	w = mg	ML/T <sup>2</sup>	980m dynes
Force	F = ma	ML/T <sup>2</sup>	$\frac{gcm}{sec^2}$ = dynes
Work	W = F · d	ML <sup>2</sup> /T <sup>2</sup>	$\frac{gcm^2}{sec^2}$ = ergs
Kinetic Energy	KE = 1/2 mv <sup>2</sup>	ML <sup>2</sup> /T <sup>2</sup>	ergs
Potential Energy	PE = mgh	ML <sup>2</sup> /T <sup>2</sup>	ergs
Power	P = w/t	ML <sup>2</sup> /T <sup>3</sup>	ergs/sec (10 <sup>7</sup> erg/sec = watt)
Momentum	p = mv	ML/T	dyne·sec
Angular Momentum	L = mvr	ML <sup>2</sup> /T	erg·sec
Unit		Symbol	Value in CGS
Atomic Mass Units		amu	1.66 x 10 <sup>-24</sup> gm
Electronic Charge		e	4.8 x 10 <sup>-10</sup> esu of charge
Electron Volt		ev	1.6 x 10 <sup>-12</sup> ergs
Million Electron Volt		Mev	1.6 x 10 <sup>-6</sup> ergs
1 amu converted to energy = 931 Mev			

## 56. SUMMARY

The reason for stressing units and basic dimensions of physical quantities is that problems are often more easily solved if proper units are used. The various units may be canceled just like ordinary numbers in the formulas, and the answer to a problem will have the units left after cancellation. As an example, find the velocity of a particle which has a certain energy  $E$ ; let  $E = 120$  ev, mass of particle = 4 amu. It is known that

$$\frac{1}{2} mv^2 = \text{energy} = E$$

$$\text{therefore } V = \sqrt{\frac{2E}{m}}$$

Substituting numbers with units and canceling units to make sure the correct units are obtained for the answer results in the following:

$$\begin{aligned} V &= \sqrt{\frac{(2)(120 \text{ ev}) \left( 1.6 \times 10^{-12} \frac{\text{ergs}}{\text{ev}} \right) \left( 1 \frac{\text{gm cm}^2}{\text{sec}^2} / \text{erg} \right)}{(4 \text{ amu}) (1.66 \times 10^{-24} \text{ gm/amu})}} \\ &= \sqrt{\frac{(2)(120)(1.6) 10^{-12}}{(4)(1.66 \times 10^{-24})} \left( \frac{\text{cm}^2}{\text{sec}^2} \right)} = 7.6 \times 10^6 \frac{\text{cm}}{\text{sec}} \end{aligned}$$

The student always should remember to keep units in the problem until the end, to avoid mistakes in unit conversions, and to avoid forgetting to square or perform some other essential mathematical operation.

## SECTION III. ATOMIC STRUCTURE

### 57. GENERAL

In order to understand various atomic energy principles, a basic knowledge of the structure of atoms is necessary. In this section, a few fundamental concepts of atomic structure will be introduced. After a historical introduction, the Bohr theory and its more modern extensions will be discussed, and an explanation will be given on how this theory will account for the building up of atoms as illustrated in the periodic table of the elements.



## 58. HISTORY

a. Among the writings of the ancient Greeks, references are found to atoms, or indivisible particles as the ultimate building blocks in all matter. Democritus apparently first suggested it, and Lucretius followed his belief. Their idea was that different materials differed in sizes, shapes, and colors of these atoms; vinegar, for example, having sharp atoms, and sugar having smoother round ones. These ideas were essentially philosophical speculation, as was much early Greek thinking, and bears no real relation to present day atomic concepts. Aristotle and most other Greek philosophers did not approve of the atomists and tended instead toward a 4-element theory, in which earth, air, fire, and water were the basic constituents of all matter. Differences in materials were considered to be due to different proportions and different modes of mixing the basic four elements.

b. During the middle ages, these ideas about matter were largely neglected, except for the few alchemists who attempted to change lead to gold by magical superstitions and the few known chemical principles. They based their hopes on the 4-element theory, trying to change the proportions and mixing of the earth, air, fire, and water in lead to those of gold or precious stones.

c. The renaissance of arts and sciences saw an increased interest in experimentation as a means of understanding nature. Galileo dropped weights from the leaning tower of Pisa. Other early scientific developments led researchers to abandon the earth-air-fire-water theory in favor of some kind of atomistic concept. The final deathblow to the old idea was dealt by the discovery that water could be broken up into two gases, oxygen and hydrogen.

d. In the early 1800's, several different people experimented with gases, and the evidence piled up in favor of a kinetic theory of matter. From the observed gas pressure, temperature, and volume laws; and from the way in which various gases combined and decomposed chemically in the laboratories, it was deduced that small molecules were the ultimate particles of matter. Hydrogen was found to have the lightest molecules, and one scientist suggested that all other molecules were made up of basic hydrogenic molecules as building blocks.

e. The first decisive experimental proof of the early kinetic theory was provided by Brownian motion. See paragraph 26. From the motion of colloidal particles in liquid suspensions, the approximate masses of molecules were determined, and these data agreed well with the values from gas laws and chemical research. The random

Brownian motion of suspended particles provides a striking demonstration of the existence of these invisible constituents of all matter.

## 59. DEFINITIONS

It is now time in this discussion to define some of the basic concepts in chemistry and atomic physics. These concepts began to be accepted in science during the 19th century.

a. An element may be defined as a substance which cannot be separated into substances different from itself by ordinary chemical means.

b. A compound is a chemical combination of different substances; e.g., sugar, water, salt.

c. A mixture is a physical mixture of different substances without their chemical combination; e.g., face powder.

d. A molecule is the smallest quantity of a substance which will normally exist by itself and retain all the chemical properties of the element or substance.

e. An atom is the smallest particle of an element which still retains all the characteristics of the element.

f. Chemical reactions are processes by which the atoms in various reacting molecules rearrange, or reattach themselves; and in this process, they may consume or release small amounts of energy in the form of heat or electrical energy. The burning of coal, oxidation, is an example of chemical reaction. The energy comes from interatomic and intermolecular binding forces. Chemical properties are thus the characteristics of substances in their various chemical processes. Among the chemical properties of an atom is its power to combine with other atoms. The combining power or valence is a measure of how many other atoms it can bind to itself by interatomic forces. Notice that this portion of the text is not dealing with details of internal structure of atoms, but only with the binding forces an atom as a whole exerts on another whole atom.

## 60. AVOGADRO'S LAW

a. The next historical development in the field of atomic physics was the law of Avogadro, first stated early in the 19th century, but understood only later in the 1850's. Avogadro, with a great deal of foresight for his time, found a means of determining the relative

masses of various molecules and atoms. As originally stated, his hypothesis was that "equal volumes of different gases at standard temperature and pressure conditions ( $0^{\circ}\text{C.}$ , 1 atmosphere) contain equal numbers of molecules." The relative masses of molecules are then determined by measuring the relative gaseous densities of substances. Measurements of certain volumes of various gases (22,400 cc.) give the following data for relative masses:

<u>Element</u>	<u>Symbol</u>	<u>Wt. of 22,400 cc. at <math>0^{\circ}\text{C.}</math>, 1 atmosphere pressure</u>	<u>Relative Atomic Wt.</u>
Hydrogen	$\text{H}_2$	2.02	1.01
Helium	He	4.00	4.00
Nitrogen	$\text{N}_2$	28.02	14.01
Oxygen	$\text{O}_2$	32.00	16.00
Fluorine	$\text{F}_2$	38.00	19.00
Neon	Ne	20.18	20.18
Chlorine	$\text{Cl}_2$	70.92	35.46
Argon	A	39.94	39.94

Since many gas molecules contain two atoms, for example,  $\text{H}_2$ ,  $\text{N}_2$ ,  $\text{O}_2$ ,  $\text{F}_2$ ,  $\text{Cl}_2$ , their weights of 22,400 cc. have been divided by 2, in order to get the relative atomic weights of these gases. It is convenient to take the weight of an oxygen molecule  $\text{O}_2$  as 32.0000, and of an oxygen atom as 16.0000 for a relative standard. This choice gives the lightest gas, hydrogen, an approximate atomic weight of 1.0. Also, oxygen is an easy gas to handle chemically in a laboratory and is a better standard than hydrogen, for example, for this practical reason. Therefore, an average oxygen atom is defined as having a mass of 16.0000 atomic mass units; and all other atomic weights are given relative to this value.

b. An amount of a gas which weighs its relative molecular weight in grams (i. e., 32 gm of  $\text{O}_2$ , or 2.02 gm of  $\text{H}_2$ , etc.) is called a gram-molecular-weight or mole of this gas. At standard temperature and pressure conditions, this amount of any gas occupies 22,400 cc. volume. According to Avogadro's law then, a gram-molecular-weight of any gas contains the same number of molecules. This

number,  $N_0$ , is called Avogadro's Number, and is measured at  $6.02 \times 10^{23}$  molecules. Another way of defining a gram-molecular-weight is that amount of substance containing  $6.02 \times 10^{23}$  molecules. This concept should be well understood.

c. The gram-molecular-weight concept has been extended to include materials where single atoms are the normal, basic, smallest particle, such as most nongaseous elements, and the noble gases, such as helium and argon. A gram-atomic-weight (gaw) of a substance is that amount of material (1) which weighs in grams the relative atomic weight; and (2), which contains  $6.02 \times 10^{23}$ , Avogadro's number, of atoms. If the distinction between atoms and molecules is understood, the distinction between gram-atomic and gram-molecular weights should also be clear.

d. A problem will be worked to illustrate the gram-atomic-weight (gaw) concept. Given that iron has a relative atomic weight of 55.85, how many grams constitute a gaw? Answer: 55.85 grams. How many gaw in 200 gm of iron? Answer:

$$\frac{200}{55.85} = 3.58 \text{ gaw.}$$

How many iron atoms in 200 gm of iron? Answer:

$$(3.58 \text{ gaw}) \left( 6.02 \times 10^{23} \frac{\text{atoms}}{\text{gaw}} \right) = 21.5 \times 10^{23} = 2.15 \times 10^{24} \text{ atoms.}$$

## 61. PROBLEMS

The student should work the following problems:

a. Given relative atomic weight of Be is 9.013, how many atoms in 2 grams of Be?

b. Given relative atomic weight of hydrogen is 1.008, how many atoms in 2 grams of H? In 1 gram? What is the mass in grams of one H atom? If  $H_2$  is the formula for a hydrogen molecule, how many molecules in 2 grams of  $H_2$ ? What is mass in grams of an  $H_2$  molecule?

c. How many grams of cadmium (atomic weight 112.4) would be needed to comprise  $8 \times 10^{25}$  atoms?

## 62. MENDELJEEF'S CHART

a. In 1858, a Russian named Mendeljeef made a tabular

arrangement of all the elements then known, and this table demonstrated a periodic law of chemical properties. He grouped the elements with similar valences in columns, and in rows according to their atomic masses. With a few exceptions, this procedure worked out well in the table. When gaps appeared in the table, he left them as gaps, assuming that other elements were yet to be discovered which would fill the gaps. On this basis, he was able to predict closely the properties of several undiscovered elements; and when these were discovered and found to have the predicted chemical properties, the periodic table was accepted widely as a correct classification system.

b. Figure 10 presents a modern version of this periodic table. The relative atomic mass of each element is listed under the symbol. The importance of this table will be apparent later, when a study is made of the actual structure of atoms. However, a few things can be learned now from the table.

(1) Since chemical reactions involve only interactions between outer parts of the atoms taking part, the similar properties of different elements must represent some kind of similarity in outer atomic structure. For example, notice in column I, Li (lithium), Na (sodium), K (potassium), Rb (rubidium), and Cs (cesium). These elements are all chemically similar in being extremely reactive, in forming strongly basic hydroxides, and in having valence +1. In column II, Be, Mg, Ca, Sr, Ba, and Ra all have normal valence +2, form hydroxides, and have other similar chemical properties. In column VII, fluorine, chlorine, bromine, and iodine show similar properties chemically. In column VIII, He, Ne, Ar, Kr, Xe, and Rn are all inert and do not react chemically. Other columns show corresponding similarity between elements. It, therefore, may be concluded that the outermost structures of atoms of elements in a given column are similar.

(2) The rows become longer for the heavier element end of the table. There are 8 elements between the similar helium and neon; again 8 between neon and argon; but 18 between argon and krypton, and 18 between krypton and xenon; then 32 between xenon and radon. This fact implied that the inner structure of atoms increases in size with the larger atoms, even though the outer details may be similar to that of smaller atoms. These deductions from the periodic table will be justified later.

### 63. RUTHERFORD'S ATOM

a. Toward the end of the 19th century, electricity began to be

	I	II	III	IV	V	VI	VII	VIII	0
1	Hydrogen 1.00794								
2	Lithium 6.941	Beryllium 9.0122	Boron 10.811	Carbon 12.011	Nitrogen 14.007	Oxygen 15.999	Fluorine 18.998	Neon 20.179	
3	Sodium 22.98977	Magnesium 24.304	Aluminum 26.98154	Silicon 28.0855	Phosphorus 30.97376	Sulfur 32.06	Chlorine 35.453	Argon 39.948	
4	Potassium 39.0983	Calcium 40.078	Scandium 44.95591	Titanium 47.88	Vanadium 50.9415	Chromium 51.9961	Manganese 54.93804	Iron 55.845	
5	Strontium 87.62	Zinc 65.38	Gallium 69.723	Germanium 72.630	Arsenic 74.9216	Selenium 78.96	Bromine 79.904	Krypton 83.80	
6	Rubidium 85.4678	Cadmium 112.411	Indium 114.818	Tellurium 127.6	Iodine 126.90547	Xenon 131.29	Cesium 132.90545	Barium 137.327	
7	Francium 223	Radium 226	Actinium 227	Thorium 232	Protactinium 231	Uranium 238.02891	Neptunium 237	Plutonium 244	

Figure 10. Periodic Table of the Elements

understood, and it was found that atoms were composed of electrically charged bits of matter. In a neutral atom, equal amounts of positive and negative electricity are stuck together, but until 1911 it was not known just how the charge was arranged. It was known that the negative charges were very light and mobile, and that they were responsible for the conduction of electricity. They had been called electrons for some time. It was also known that heavy, positively charged particles would spontaneously be ejected from certain atoms in the radioactivity process. These were called  $\alpha$  particles and were shown to be helium atoms which had lost their negative charge (i.e., doubly ionized He). In 1911, Rutherford showed that the atom is built of two basic parts, a small but heavy positive nucleus, and a light negative cloud of extranuclear charge. Figure 11 shows the Rutherford atomic picture.

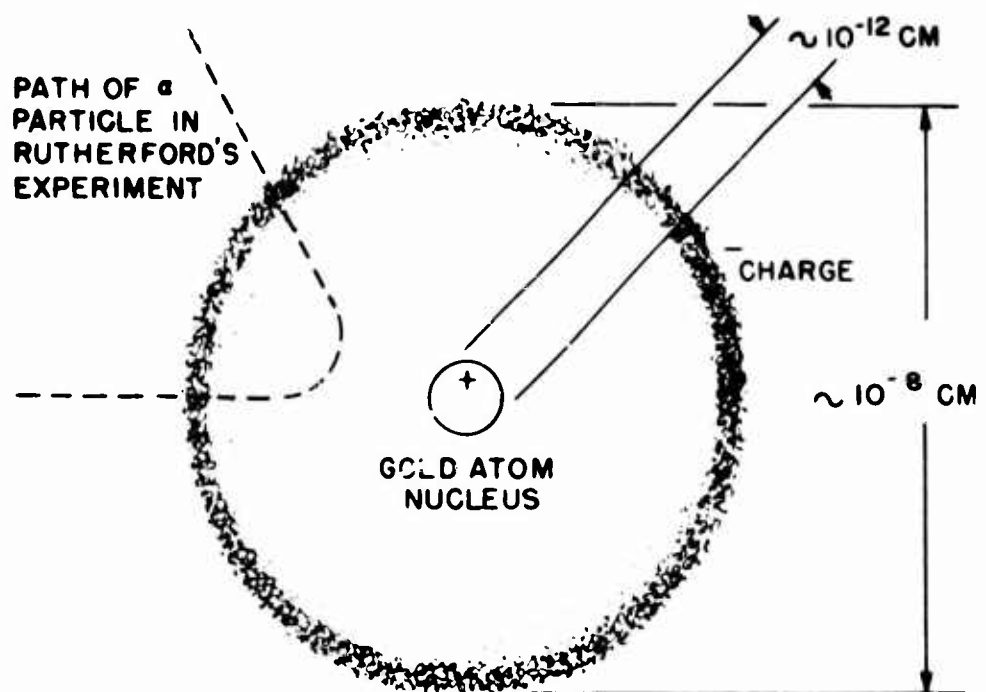


Figure 11. Rutherford's Atom

b. This model was arrived at by experimentation.  $\alpha$  particles from radium bombarded a thin gold foil. Most of them passed through with only slight deflection, but some were deflected by large angles--up to 180 degrees. This fact could only be interpreted as a process in which these  $\alpha$  particles struck a heavy, positively charged bit of matter. From these and other scattering experiments, the relative sizes and masses of the nucleus and the electronic cloud were calculated. Almost all the mass of the atom is concentrated in the nucleus, which

has a diameter of about  $10^{-12}$  cm. The diameter of the whole atom, the electron cloud, is about  $10^{-8}$  cm.

#### 64. BOHR'S ATOM

a. By the first decade of the 20th century, physicists were in possession of a great mass of data regarding atomic phenomena, but without a really comprehensive theoretical interpretation of it. Among the more significant of these facts was the spectroscopic data on the nature of light emitted from various substances. If the light from electrical discharges in gases or from incandescent material is analyzed into its component wavelengths by a prism or other spectrograph, a series of definite colored lines is found. Each element is characterized by its own spectral lines. In some cases, a series of lines with regular spacings occur on a spectrograph. See figure 12.

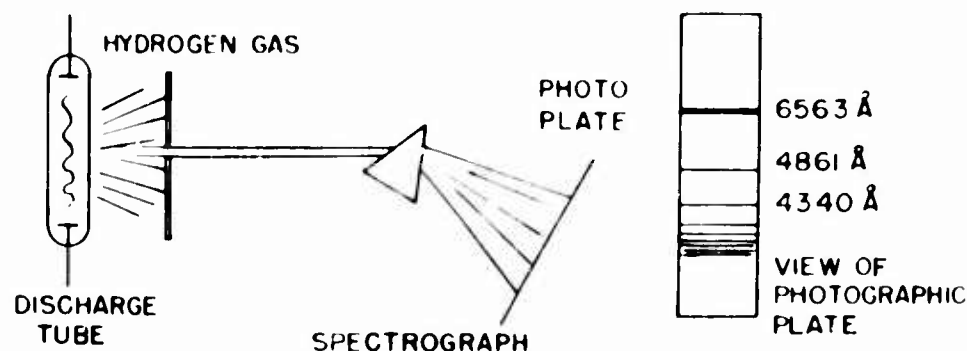


Figure 12. Spectrography

With sodium, two closely-spaced lines were found at 5890 Å and 5896 Å. With hydrogen, several series of lines were found with wavelengths varying from ultraviolet to infrared. These discrete spectral lines suggested that atoms were so constructed that light was emitted in definite amounts of energy when the atoms were excited.

b. As early as 1903, Planck had shown that electromagnetic radiation could be thought of as being absorbed and emitted in discrete quanta, with energy  $E = h\nu$ . See paragraphs 41 and 52. Also, the photoelectric effect, interpreted by Einstein in 1908, demonstrated that light of various wavelengths had various energy quanta, or photons, as postulated by Planck; and that light intensity did not depend on the energy of the photons, but upon the number of photons. It was



a consideration of such facts as these that led Bohr to make three postulates for a new theory in 1913.

c. Bohr assumed a nuclear atom, as has been discussed. He postulated:

- I. The electrons outside the nucleus exist in stable circular orbits.*
- II. The angular momentum of an electron in its orbit may assume only certain definite values, integral multiples of  $h/2\pi$ , (i.e., angular momentum =  $nh/2\pi$ , where  $n = 1, 2, 3$ , or other whole number;  $n$  is called the principal quantum number.)*
- III. Light is emitted or absorbed in transitions or quantum jumps between the various orbits.*

d. The first postulate was hard for some classical physicists to accept, since it stated that the accelerated electron need not radiate energy as required by the classical radiation theory of Maxwell. In the Bohr theory, the electron is centripetally accelerated without losing any of its energy. From this postulate, a relation may be set down between the forces acting on the electron of a hydrogen atom:

$$\frac{mv^2}{r} = \frac{e^2}{r^2}.$$

In the above equation,  $mv^2/r$  is the centrifugal force,  $e^2/r^2$  is the electrostatic attractive force, and these two forces must balance if a stable orbit is to exist.

e. The second postulate is the quantization rule by which the discrete quantum nature of the theory is introduced. Mathematically,

$$mvr = \frac{nh}{2\pi}.$$

Here  $mvr$  is the angular momentum of the electron in an orbit of radius  $r$ . The quantization rule is responsible for the fact that the possible orbits have only certain specific radii. To each orbit, there corresponds a certain total energy of the atom, which is the energy level of the atom.

f. The third postulate explains how radiation is emitted. The atom may be put into an energy level of higher than normal energy by

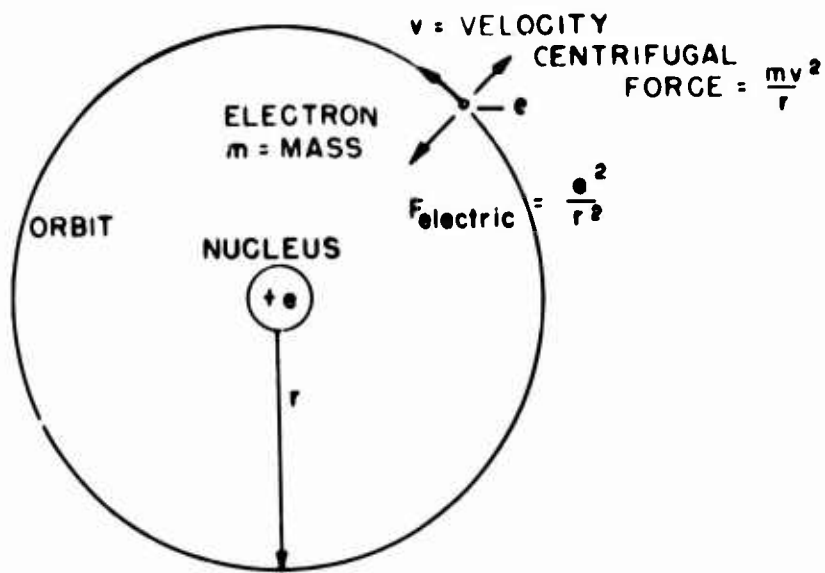


Figure 13. Bohr's Atom

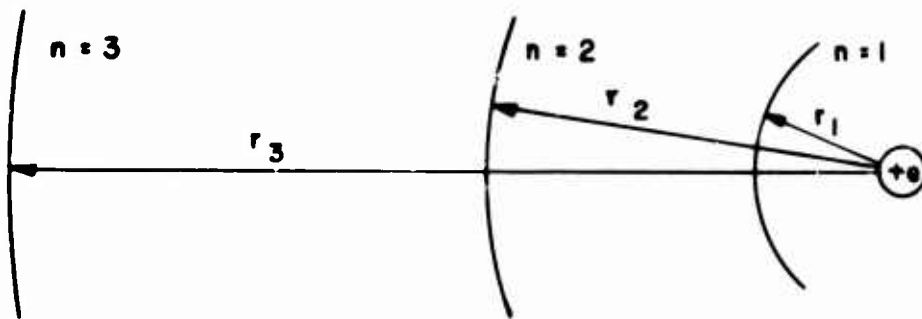


Figure 14. Orbit Radius

some means. Then as it jumps back to a lower energy level, radiation is emitted. The frequency  $\nu$  of the emitted light is given by:

$$h\nu = W_{\text{initial}} - W_{\text{final}}$$

where  $W_{\text{initial}}$  is the energy of the higher level, and  $W_{\text{final}}$  is the lower energy level.

g. Algebraic manipulation of postulates I and II leads to the expression:

$$r_n = n^2 \left( \frac{h^2}{4\pi^2 m_e e^2} \right)$$

for the radius of the nth orbit in hydrogen.

From the information contained in figure 14,

$$r_1 = 1^2 \left( \frac{h^2}{4\pi^2 m_e e^2} \right) = 5.29 \times 10^{-9} \text{ cm.}$$

$$r_2 = 2^2 (r_1) = 4r_1$$

$$r_3 = 9r_1$$

Note that the orbit radius increases rapidly for the higher energy levels.

h. The total energy of the hydrogen atom, when its electron is in an orbit n, is partly kinetic and partly potential. The kinetic energy comes from the motion of the electron, the potential energy from its position in the nucleus' electric field. The total energy may be written as:

$$W = - \frac{e^2}{2r}.$$

$$\text{Thus: } W_n = \frac{2\pi^2 m_e e^4}{h^2 n^2}.$$

The minus sign indicates binding; that is, work must be done to separate the electron from the nucleus. An energy level diagram is often plotted to illustrate the atom.

i. The student should notice that these are the only possible energies for the atom to have, and that the atom is in only one level at a time. Obviously it could not possess 2 energies at once, nor could 1 electron be in 2 orbits at once. For a given value of n, however, the energy is a certain definite amount.

j. From this energy level diagram, which shows energy as a

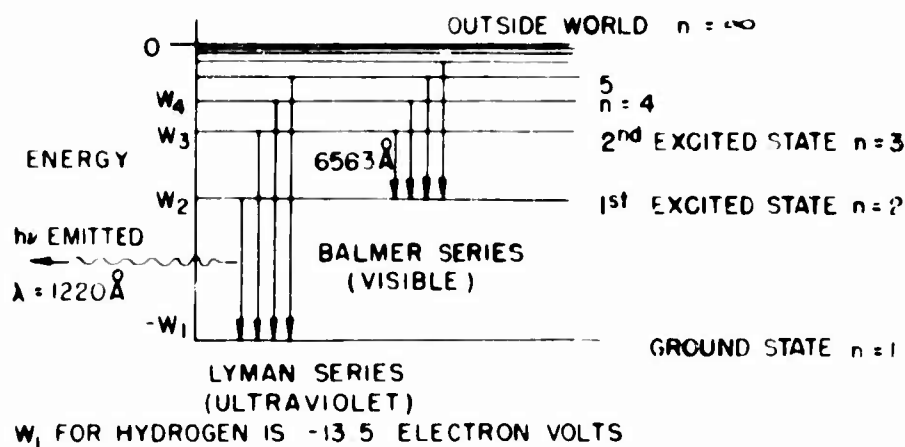


Figure 15. Energy Level Diagram

function of  $n$ , the processes of emission or absorption of light, as discrete quanta, may be seen. The lowest state of the atom is the normal one, the ground state,  $n = 1$ . If the atom is excited to a higher state, say  $n = 2$ , a transition from  $n = 2$  to  $n = 1$  may occur in which light energy is emitted. The frequency  $\nu$  is given by:

$$\begin{aligned}\Delta E = h\nu &= W_{\text{initial}} - W_{\text{final}} \\ &= \frac{2\pi^2 me^4}{h^2} \left( \frac{1}{n_f^2} - \frac{1}{n_i^2} \right) = \frac{2\pi^2 me^4}{h^2} \left( \frac{1}{1^2} - \frac{1}{2^2} \right).\end{aligned}$$

In general, for a transition from  $n_i$  to  $n_f$ , the wavelength  $\lambda$  of the radiation involved is given by

$$\begin{aligned}\frac{1}{\lambda} &= \frac{\nu}{c} = \frac{2\pi^2 me^4}{ch^3} \left( \frac{1}{n_f^2} - \frac{1}{n_i^2} \right) \\ &= 1.09 \times 10^5 \left( \frac{1}{n_f^2} - \frac{1}{n_i^2} \right) \text{ cm}^{-1},\end{aligned}$$

where  $1.09 \times 10^5$  is called  $R$ , the Rydberg constant. For example, the wavelength of light emitted in transition  $n = 2$  to  $n = 1$  is  $1220 \text{ \AA}$ .

$$\begin{aligned}\frac{1}{\lambda} &= 1.09 \times 10^5 \left( \frac{1}{1} - \frac{1}{4} \right) = 0.817 \times 10^5 \text{ cm}^{-1} \\ \lambda &= 1220 \text{ \AA}\end{aligned}$$

k. A spectral series results from a series of transitions which all end on the same level. The series of transitions, 2 to 1, 3 to 1, 4 to 1, etc., give a series of ultraviolet spectral lines called the Lyman series. The transitions ending on level  $n = 2$  (i. e., 3 to 2, 4 to 2, 5 to 2, etc.) give the Balmer series, which is in the visible region of the spectrum.

l. In this connection, the student should again be reminded that 1 atom may be in only 1 state at a time, and therefore a single atom may make only 1 transition at a time. The observed series of lines are the quadrillions of atoms which are all being excited to various levels and making various transitions, resulting in photons of a large number of different wavelengths. In other words, the laboratory experiment is done with large numbers of atoms, and statistical behavior is to be expected.

m. Absorption of light takes place by the transition of an atom from a lower to a higher energy level. This fact explains the discrete absorption spectra, and the fact that light is absorbed in quanta.

n. The results of the Bohr quantum theory of the atom will now be summarized. The hydrogen atom was pictured as a miniature solar system with a heavy positive nucleus and a light negative satellite electron which could assume only certain radii. These possible radii of orbits were governed by the quantum condition, and a definite total energy of the atom was associated with each possible orbit. Thus, the atom is described as being in a certain state, depending on the principal quantum number  $n$ . The most stable state is the ground state, having the lowest energy. Excited states may also exist, if some means is provided to add sufficient energy to the atomic system. When a transition occurs between states, a photon of light energy may be involved. If an atom in an excited state relaxes into a lower energy state, the difference in energy of the two states is emitted as a light quantum. This explains line spectra. An atom in a ground state may absorb a quantum of the proper energy and go into an excited state. This explains absorption phenomena. If the electron is kicked out of the atom entirely, it has been excited to  $n = \infty$  and the atom is said to be ionized. The energy of an ionized state is taken as zero on the energy level diagram, since the free electron feels no force on it from the nucleus. The bound states of the electron all possess a negative energy on the diagram, with the ground state having the most negative energy since it is most tightly bound.

## 65. BOHR'S THEORY EXTENDED

a. The Bohr picture accounted for most of the 1913 facts, but it

could not give a good explanation for any but hydrogen-like (one electron) atoms. Nor could it explain the relative intensities of spectral lines; that is, the relative probabilities of different possible transitions. Another inadequacy was that it did not explain the fine structure of spectral lines. By this is meant that often 2 or 3 spectral lines are grouped very closely on the spectrograph, so that they appear as 1 line on any but the most sensitive equipment. This structure of a spectral line implied that the energy levels in the Bohr theory were not simply one state, but were actually split into several closely lying energy states.

b. In the years following 1913, these inadequacies were investigated, and Bohr's theory was extended. Elliptical orbits were postulated, and these were found to give sufficient variations in level energies to allow for some of the observed fine structures. Another approach was to assume that the electron was spinning on its own axis with an intrinsic angular momentum,

$$h/4\pi \left( \frac{1}{2} \times \frac{h}{2\pi} \right).$$

This spin angular momentum, or spin, then introduced a small amount of magnetic moment into the atom, and interaction of this spin magnetic moment and the magnetism generated by the orbital electronic motion was sufficient to account for the level splitting. In this new theory, with spin, the total angular momentum was required to be quantized. If  $j$  is total angular momentum quantum number,  $j = l + s$ , where  $l$  is orbital and  $s$  is the spin-quantum number. It was found that:

$$s = \pm \frac{1}{2},$$

and  $l$  could be any integer up to  $n$ , the principal quantum number. This model<sup>1</sup> of the atom accounted for many phenomena, including two electron atoms, Zeeman and Stark<sup>2</sup> effects, level splittings, and some of the transition probabilities; but of course several new quantum numbers were introduced as well. These numbers,  $n$ ,  $l$ ,  $j$ ,  $s$ , were brought into the theory in a quite empirical way, to explain observations.

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<sup>1</sup> The vector model of the atom.

<sup>2</sup> Zeeman effect is the splitting of spectral lines when the atom is in a magnetic field. Stark effect is the same for an electric field.

## 66. QUANTUM MECHANICS<sup>1</sup>

a. Entirely different approaches to the subject of atomic theory were made independently by Schroedinger and Heisenberg. The resulting theory, called quantum mechanics, is a statistical one. It accounts for transition probabilities between states, for the small differences in energy of close lying states; in short, for the correct prediction of all observable physical quantities. The quantum numbers arise quite naturally in this theory and do not result simply from arbitrary assumptions regarding atomic structure. However, no real picture of an atom is given by quantum mechanics as it was given by Bohr's theory.

b. Several quantum numbers arise naturally from the new quantum theory. They are  $n$ , the principal quantum number;  $l$ , the orbital angular momentum quantum number;  $m$ , the magnetic quantum number, which describes the splitting of energy levels when a magnetic field is applied to an atom; and  $s$ , the electron spin quantum number. The following table shows the allowed values for these numbers:

$$n = 1, 2, 3, 4, \dots \text{any integer}$$

$$l = 0, 1, 2, \dots, n - 1, \text{integers up to, but not including } n.$$

$$m = -l, -l + 1, \dots, 0, 1, 2, \dots, l, \text{all integers, positive and negative between } -l \text{ and } +l.$$

$$s = \pm \frac{1}{2}.$$

c. Each possible state of an atomic system is thus characterized by a set of four numbers,  $n, l, m, s$ . The ground state of hydrogen, for example, is given by:

$$n = 1$$

$$m = 0$$

$$l = 0,$$

$$s = +\frac{1}{2} \text{ or } -\frac{1}{2}.$$

Excited states, with the electron in a larger orbit, will be given by larger  $n$  values. The first excited state in hydrogen has  $n = 2$ . Then

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<sup>1</sup> Paragraphs 65 and 66 are presented for the benefit of those students interested in additional information on this subject and are not presented in the formal course of instruction.

there are possible variations in energy of this state, corresponding to  $l = 0$  and  $l = 1$ . For  $l = 0$ ,  $m = 0$ , and  $s = \pm 1/2$ . For  $l = 1$ ,  $m = -1$ ,  $0$ , or  $+1$ , with  $s = \pm 1/2$  possible in each state. This means there could be eight separate splittings in the energy level  $n = 2$ . Transitions from these various split levels to the ground state cause fine structure in the spectra.

## 67. HOW ATOMS ARE BUILT

a. It has been mentioned that the newer quantum theory allows a description of atoms with more than one electron. This will not be attempted here with all the mathematical apparatus of the new theory. Rather, this text will use the Bohr picture and borrow only the quantum numbers from the modern theory. Only the ground states of the various atoms will be considered.

b. A hydrogen atom has a positively charged nucleus and a single electron. In its ground state then, it must look something like figure 16.

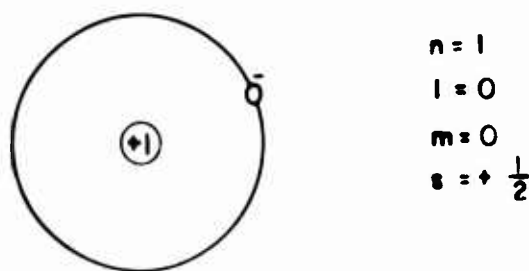


Figure 16. Hydrogen Atom

$s = +1/2$  indicates that the electron spin vector is parallel to the orbital angular momentum vector.

c. To make a helium atom requires 2 positive charges on the nucleus, as well as some additional mass there, and 2 orbital electrons. They may arrange in the ground state like figure 17.

d. To make a lithium atom, 3 charges on the nucleus are needed, plus more mass and 3 electrons. One might think that the third electron could have  $n = 1$  for its lowest energy, but a basic principle of quantum mechanics must be evoked: No two electrons may have the same identical set of quantum numbers. This is the Pauli exclusion principle. It shows that in a lithium atom the third electron cannot



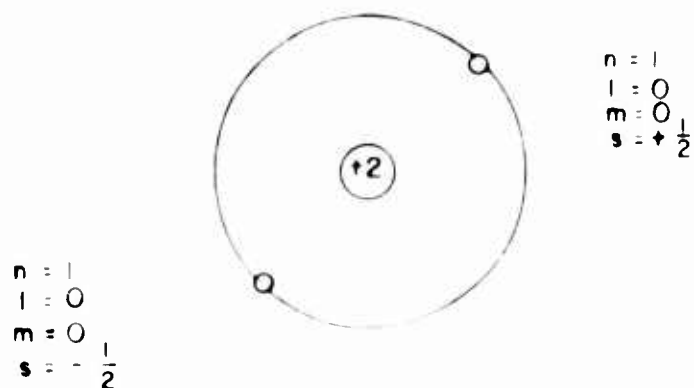


Figure 17. Helium Atom

have  $n = 1$ , but must be in an  $n = 2$  state. The ground state of lithium thus may be pictured as in figure 18.

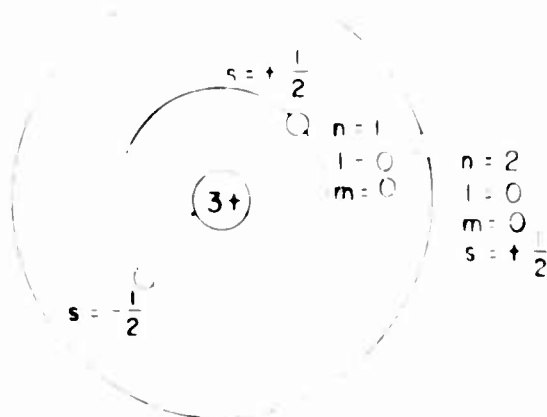


Figure 18. Lithium Atom

e. To make a beryllium atom, a positive charge and some mass must be added to the nucleus and an electron to the  $n = 2$  shell. See figure 19.

f. To make boron, a fifth charge plus mass is added to the nucleus, and a fifth electron is placed in the outer structure. The  $n = 2$  and  $l = 0$  states are used up, but  $n = 2$  with  $l = 1$  states are available, so the boron atom in its ground state looks something like figure 20.

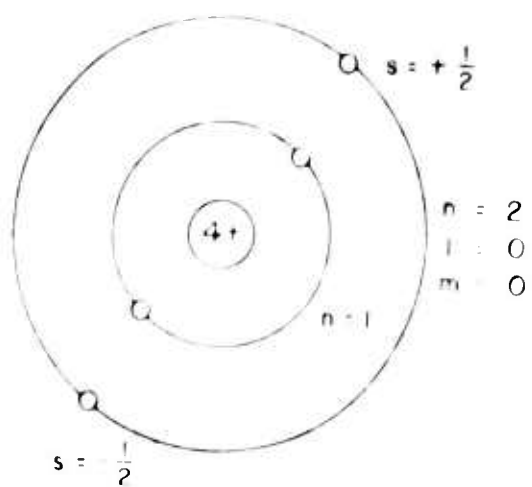


Figure 19. Beryllium Atom

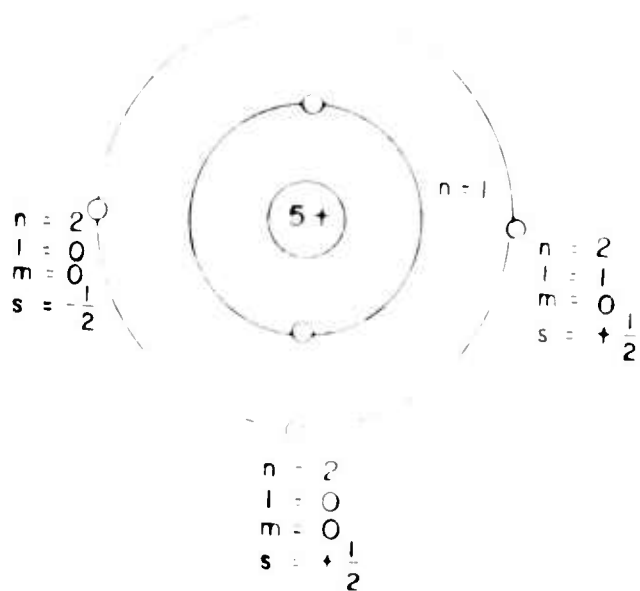


Figure 20. Boron Atom

g. As an upward progression is made in the periodic table, it is found that electrons continue to be added in conformity with the exclusion principle. The periodicity of chemical properties is explained by the similarity in outermost electron configurations. The chemical inertness of certain elements is explained by the completed shells of electrons which tend not to lose or to add electrons. The longer periods in the table are explained by the filling of inner shells with more and more electrons as the size of the atoms increases.

#### 68. SUMMARY

The student should remember Bohr's three postulates, the general outline of the old Bohr theory, and the success it had in explaining various phenomena. He should recognize its inadequacies and how the newer theory obviates them. He should be familiar with the periodic table and understand in general terms why the elements may be so grouped. He should know what the various terms, atom, element, chemical property, atomic weight, and gram atomic weight mean; and be able to do problems with gram atomic weights which require calculation of the numbers of atoms in given amounts of material. He should remember that the preceding section has dealt only with the electrons in the atom. The next section will be devoted principally to basic nuclear structure.

#### 69. PROBLEMS

a. Using the periodic chart, find how many grams of bismuth are in 1.8-gram atomic weights. How many atoms? How many electrons are in this amount of material?

b. How many atoms are in 1 cubic centimeter of aluminum which has a density of  $2.7 \text{ gm/cm}^3$ ? How many electrons per  $\text{cm}^3$ ?

c. What wavelength of light is admitted in a hydrogen atom quantum jump from  $n = 3$  to  $n = 2$ ? In what part of the spectrum does it lie?

## CHAPTER 4

### NUCLEAR PHYSICS

#### SECTION I. NUCLEAR STRUCTURE

##### 70. GENERAL

The last section described in some detail the electronic configurations in atoms. While these considerations are interesting and occupied physicists' attention for many years, the detailed results are not as useful in this course as the general picture. Chemical and light photon energies are generally low and in the electron-volt range, while nuclear energies are in the Mev range. This text is more concerned with the larger nuclear energies. This section will deal with basic nuclear structure and will apply some of the quantization concepts to introduce nuclear phenomena.

##### 71. ATOMIC NUMBERS AND MASS UNITS

a. At the turn of the century, it was discovered that many substances spontaneously emitted various types of rays. These radiations were shown to come from the nuclei of atoms. By careful experimentation and some good fortune, it was found that a few atoms actually could be transmuted or changed by allowing certain of these radiations to bombard them. It was shown that hydrogen nuclei, or protons, are responsible for the positive charge present on all nuclei. Thus, in a sense, the guess in the early 1800's that all matter is made up of hydrogen atoms was shown to be correct. However, it was known that more mass units than charge units were present in nuclei. At first it was thought that a proton and an electron were neutralized within the nucleus to provide mass without charge. It is known today that this is not so.

b. In 1932, Chadwick found a very penetrating radiation in certain nuclear experiments. He correctly attributed this to a new particle, neutral in charge, and with a mass about equal to a proton mass. This particle he named the neutron.

c. It is now known that the atomic nucleus contains two types of particles, protons and neutrons. Protons carry a unit positive electric charge and have a mass of 1.00758 amu. Neutrons carry no charge and have a mass of 1.00894 amu. These two types of particles are bound together by nuclear forces.

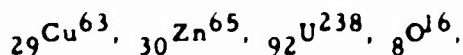
d. In the discussion of the periodic table, it was stated that originally Mendeljeef had ordered the elements according to their relative atomic weights. This ordering gave several irregularities in the chemical properties. For example, argon is heavier than potassium, and this inert gas should correspond to an active metal if the mass order is used. In 1914, the correct way to order the periodic table was shown by Moseley to be by the number of protons in the nucleus, not by its total mass. This number is called the atomic number of the atom, and the symbol  $Z$  is used to indicate it.

e. If there are  $Z$  protons in the nucleus, then there must be  $Z$  electrons in the orbits of a neutral atom. For this reason,  $Z$  is the quantity which determines the chemical properties of an element. For example, a copper atom has 29 protons in its nucleus and 29 electrons in its orbits.

f. It is known that there are more mass units than charge units in the nucleus. Since protons have about one mass unit each, neutrons must also exist in the nucleus which have a mass unit but no charge. The total number of massive particles in the nucleus (i. e., the number of protons plus neutrons) is called the atomic mass number  $A$  of the nucleus. Thus, the number of neutrons in a nucleus with mass number  $A$  and atomic number  $Z$  is  $A - Z$ . The usual way of indicating an atom or nucleus which has atomic number  $Z$  and atomic mass  $A$  is



where  $X$  is the chemical symbol for the element. For example,



represent particular atoms with their atomic numbers and mass numbers specified.

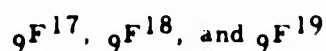
## 72. ISOTOPES, ISOBARS, ISOMERS

a. In nature, there are many instances of an element having different atomic masses. For example, two types of copper are found,



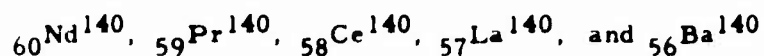
These two types behave nearly identically, since they are both copper, with 29 protons and 29 electrons.

However,  ${}_{29}\text{Cu}^{65}$  has 36 neutrons while  ${}_{29}\text{Cu}^{63}$  has only 34 neutrons in the nucleus. These two atoms are said to be isotopes. Isotopes (from iso, meaning "same," and tope, meaning "place", i.e., the same place in the periodic table) are atoms which have the same atomic number Z, but different atomic mass numbers, A.



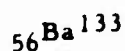
are examples of isotopes of fluorine.

b. Atoms which have the same total number of nuclear particles but different numbers of protons are called isobars. (Baros means "weight.") Isobars have the same A, but different Z's. They are different chemical elements.



are examples of isobars. Isobars are important to detailed studies of nuclear theory.

c. In some cases, two atoms may have the same number of protons and the same number of neutrons, but differ in the energy level of their nuclei. Eventually the higher energy level nucleus will convert itself to a lower energy level nucleus of the same particle composition by isomeric transition. Different energy states of the same nucleus are called isomers or isomeric states of the nucleus. For example,



exists in 2 isomeric forms, 1 of which decays into the other.<sup>1</sup>

d. The different isotopes of an element behave nearly identically in chemical reactions. Therefore, one cannot separate isotopes

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<sup>1</sup> This information is obtained from the Chart of the Nuclides published by the Knolls Atomic Power Laboratory, General Electric. The student would do well to examine this chart carefully, noticing isotopes, isobars, isomers, and notations.

chemically.<sup>1</sup> In measuring atomic weights by chemical means, the observed value for an element will be an average value over all of its isotopes. Copper has a chemically measured atomic weight of 63.54. Natural copper occurs with 71 percent Cu-63 and 29 percent Cu-65.

e. The above fact has caused some confusion in the atomic weight system, since the choice of oxygen as a standard for chemical weights was made before isotopes were known. Fortunately, oxygen occurs in essentially only one isotope,<sup>2</sup>



since the other isotopes,  ${}_8\text{O}^{17}$  and  ${}_8\text{O}^{18}$ , constitute less than 0.037 percent of chemical oxygen. Therefore, the definition used so far in this book, given in paragraphs 60a and 54, is essentially correct, although physicists generally take an amu as equal to 1/16 the mass of an



atom. Only when dealing with the fifth decimal place in calculations would the difference between the chemical and physical atomic mass scales cause any discrepancy.

### 13. NUCLEAR FORCES

The neutrons and protons in a nucleus are bound together very tightly by nuclear forces. These forces are stronger than the electrostatic repulsion between protons, and they exhibit several striking peculiarities:

a. Nuclear forces are short range, in that they apparently do not act except within distances of about  $2 \times 10^{-13}$  cm. When two nucleons (a neutron or a proton) approach each other, no nuclear force is exerted until the separation is about  $2 \times 10^{-13}$  cm, and at this distance the force becomes active.

b. Nuclear forces are strong, that is, they bind nucleons tightly. To separate a bound neutron and proton, as for example a H-2 nucleus, requires about 2.2 Mev of energy. To pull a neutron out of a heavier element requires up to 8 Mev. Compare this with the few ev

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<sup>1</sup> With certain difficult chemical techniques, using ion exchange reactions, a small degree of isotope enrichment can be accomplished. In general the statement in the text is true.

<sup>2</sup> This information, too, comes from the Chart of the Nuclides.

required to remove an electron from an atom. The potential energy of a nucleon in the field of another may be as high as 25 Mev.

c. Nuclear forces are charge independent; that is, they act equally between proton groups, neutron groups, and proton-neutron groups.

d. Nuclear forces are attractive, but saturable; that is, a given nucleon may attract strongly up to three other nucleons, but a fourth will be repelled. This repulsion is related to the exclusion principle stated in paragraph 67d.

e. Nuclear forces are spin dependent, showing tighter binding between two nucleons whose spins are parallel than between two whose spins are antiparallel.

#### 74. ENERGY OF THE NUCLEUS

a. An exactly correct picture of the nucleus is harder to find than one for the electronic parts of the atom. Quantum mechanical rules of thought seem to apply, but the science of detailed nuclear theory is still largely empirical. Experimenters have verified that the total energy of the nucleus is quantized; that is, restricted to certain definite values. Some evidence exists for a type of shell structure similar to the electron shells with extra stable nuclei existing with closed shells. Helium, carbon, oxygen, calcium, tin, and lead isotopes seem to show extra stable nuclear construction. Since the theory of the shell model becomes quite detailed with further description, the discussion will stop at this point. The student should know that discrete energy levels exist in the nucleus, and that these levels are not as regular or easy to describe as in the electronic levels.

b. If a nucleus is excited into any energy level other than its ground state, it will decay to its ground state with the emission of some radiation. This radiation may be a photon of electromagnetic energy, in which case it is called a gamma ray. In some cases, the nucleus will make a transition to another type of nucleus, giving up a beta particle, which may be either an electron or a positron (positive electron). In other cases, a nucleus may find itself able to get into a lower energy state by ejection of a bound group of 2 neutrons plus 2 protons, called an alpha particle, designated:



These three types of radioactivity were discovered long ago, but they now can be understood in terms of the energy level structure of the nucleus.



c. The nucleus can have energy transferred to it in much the same way as energy can be transferred to the orbital electrons of an atom. We are not interested in the manner in which the energy is transferred but in the fact that the nucleus can be excited and that the nucleus can remain in a metastable excited state. This excited state of a nucleus is an isomeric state.

d. The nucleus is excited to states of definite energy content much the same way as an orbital electron is excited to states of definite energy content.

e. Just as in the case of the orbital electrons, when the excited nucleus returns to a less excited state or to the ground state, electromagnetic radiation is emitted. The energy transitions for the nucleus are much greater than for the orbital electrons so that the radiation obtained is usually of higher frequency. In the case of nuclear emission, it is called gamma radiation.

f. Since the nucleus has definite, or discrete, energy states, we can construct an energy level diagram. Such an energy level diagram has been constructed for Ce-140 and is illustrated in figure 21. Due to these definite levels, the gamma ray spectrum is usually discrete, that is, there are only certain definite energies (equal to the difference between two levels) that the gammas from a given nuclide may have.

g. One important item should be noted about nuclear energy transitions as compared to electronic energy transitions. In the electronic case, the transitions are definitely associated with a definite orbital electron. Such is not the known case for nuclear energy transitions, that is, the energy levels are associated with a nucleus and not with a definite nucleon in the nucleus.

## 75. NUCLEAR STABILITY

a. Just why certain nuclei are more stable than others is not completely understood. However, one contributing factor is known to be the neutron to proton ratio,

$$\frac{A - Z}{Z}.$$

The n/p ratio is important to stability because of the slight tendency of protons to repel each other even though bound into a nucleus by nuclear forces. The picture of the nucleus of an atom may be thought of as being something like figure 22. Each ball represents a nucleon and its sphere of action.

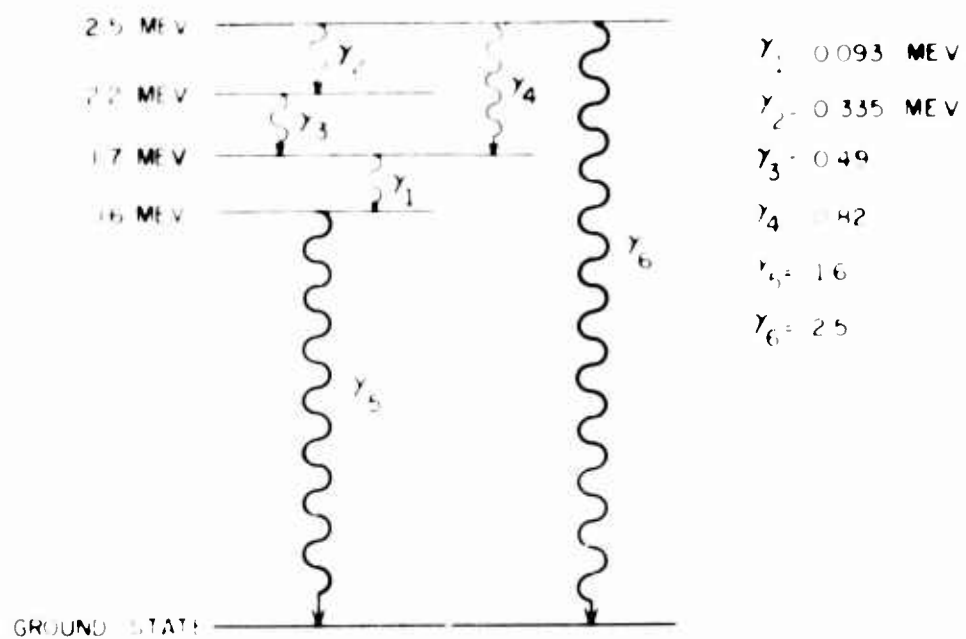


Figure 21. Nuclear Energy Level Diagram for Ce-140

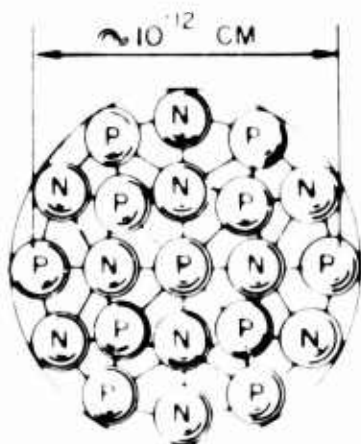


Figure 22. Nucleus of Atom

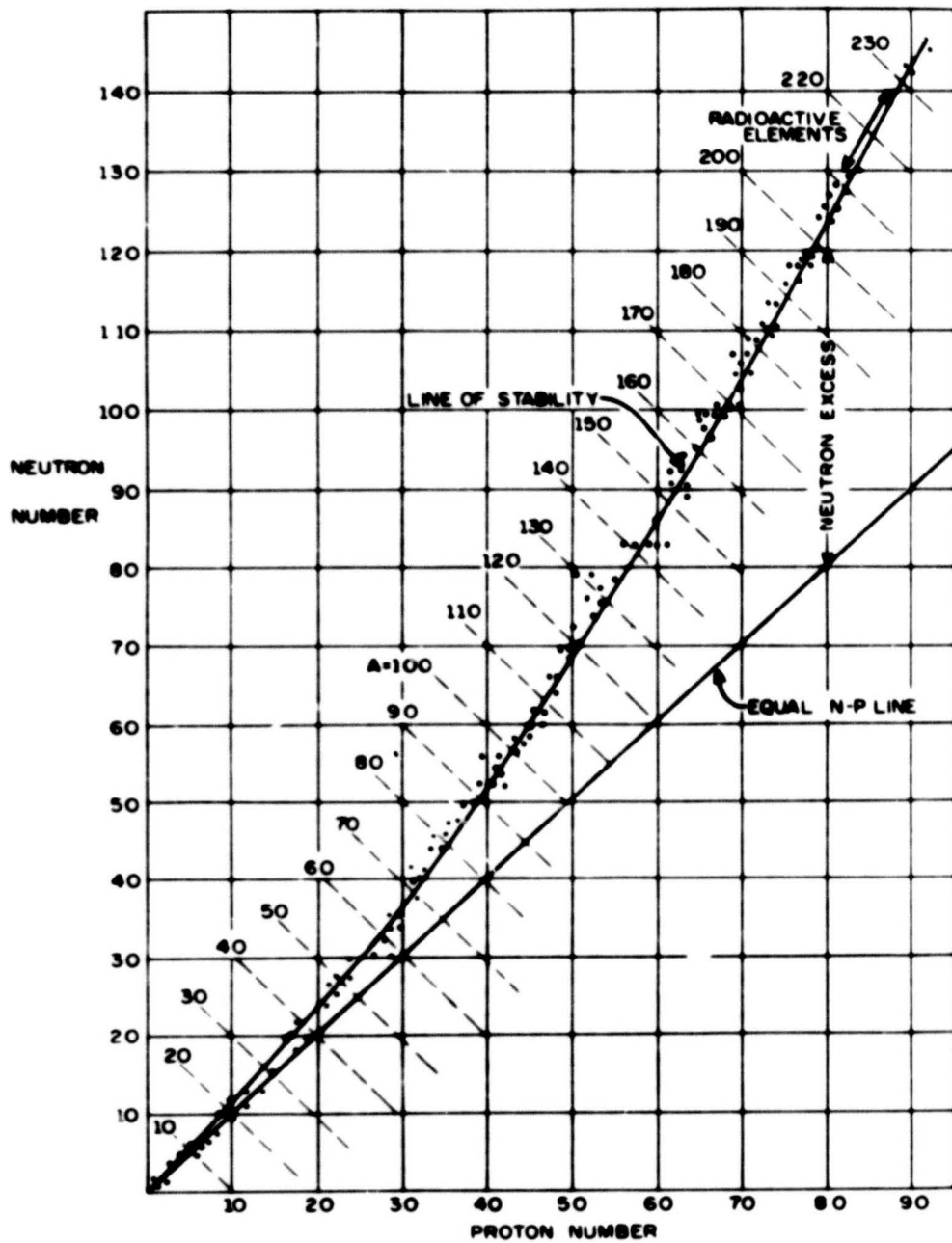


Figure 23. Nuclear Stability

Because of their charge, the protons will tend to separate from one another. However, because of saturation and spin dependence in the forces, the protons cannot all be on the nuclear surface. To take up nuclear space, then, an excess of neutrons will be required, since these particles will experience no charge repulsion, but only nuclear forces. Protons on opposite sides of the nucleus will in fact experience no direct nuclear force, but only an electrostatic force. However, they are bound nuclearly to common intermediate internal nucleons, and so the small electric repulsion is not sufficient to expel them. In other words, since the binding energy of a nucleon is greater than the electric repulsive potential energy, the nucleus stays together.

b. When there are too many protons in a nucleus, however, the nucleus generally will remain bound, but it may be that a lower energy state will exist for an isobar. In each case, the proton finds it desirable to change identity, becoming a neutron, and kicking off its charge in the form of a positive beta particle (positron). Therefore,  $\beta^+$  radioactivity results from too low an n/p ratio. In a similar process, and a more common type of radioactivity, a neutron may change itself into a proton and into a negative beta particle (electron) which is ejected. This type of change results from the fact that there are too many neutrons in the nucleus, and there is a lower energy state for the isobar with a lower n/p ratio. Therefore,  $\beta^-$  radioactivity results from too high an n/p ratio. In these ways, a nucleus can adjust its n/p ratio for maximum stability.

c. When the n/p ratios for all the various elements which exist in nature are examined, it is found that the ratio varies from 1.0 for light elements to 1.6 for heavy nuclei. The region of stable nuclei is represented by the shaded region on the curve, figure 23. At  $Z = 84$ , the elements begin to be naturally radioactive, indicating some instability. If an element is made by man in a laboratory, its n/p ratio will determine its stability and mode of decay. If it falls within the region of stability, it will be stable. If to the right, it will be  $\beta^+$  active; if to the left,  $\beta^-$  active. Gamma rays may be associated with these  $\beta$  emissions.

d. The  $\alpha$  particles are most common from the naturally radioactive heavy nuclei, which indicates that their instability is at least partly due to their large mass. In a emission among these elements, the n/p ratio does not change much. Apparently 2 neutrons and 2 protons occasionally get bound together in a little mutually-exclusive group within the nucleus, then find their way out into the world as an  $\alpha$  particle, leaving the nucleus in a somewhat lower energy state. These radioactive decay processes will be discussed more in chapter 5.

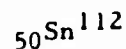
## 76. SUMMARY

a. The student should remember that  $A$  is the atomic mass number and indicates the total number of particles in the nucleus, that  $Z$  is the atomic number, or number of protons in the nucleus, and, therefore,  $A - Z$  is the number of neutrons in a nucleus. He should remember that isotopes are chemically similar atoms, having the same  $Z$ , but having a different  $A$ , and that isobars have the same  $A$ , but different  $Z$ 's. Isomers are different energy states of a nucleus with a given  $A$  and  $Z$ . He should remember and understand the general features of nuclear force properties and the nuclear energy levels resulting from these forces.

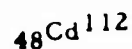
b. The several succeeding sections will describe phenomena which are readily explained in terms of these nuclear energy levels and in the light of material presented here. Therefore, the student should be familiar with this information.

## 77. PROBLEMS

a. Using the periodic chart, figure 10 in paragraph 62, find all the isotopes of tin. Find natural isobars on the chart for at least six of the tin isotopes; e. g.,



has the isobar



b. Calculate the  $n/p$  ratio for Ca-40, Zr-92, Xe-131, and Pu-239.

## SECTION II. PARTICLES

### 78. GENERAL

This section is intended to acquaint the student with the properties of the basic particles involved in nuclear physics. In addition to neutrons, protons, and electrons, combinations such as the deuteron, triton, alpha, and other particles of theoretical and experimental interest in the field of physics will be discussed. A description of the properties of three important elementary particles will be given first.

## 79. DESCRIPTION

a. The proton is the nucleus of a hydrogen ( ${}_1\text{H}^1$ ) atom. It is a basic building block in all nuclei. It has a positive electric charge of  $+e$ ,  $4.80 \times 10^{-10}$  esu; a mass of 1840 electron masses,  $1.66 \times 10^{-24}$  gm, or 1.00758 amu. It exerts nuclear forces on other nucleons. The symbol for a proton is  ${}_1\text{p}^1$  or  ${}_1\text{H}^1$ , or simply p.

b. The neutron is electrically neutral and has a mass of about 1840 electron masses,  $1.66 \times 10^{-24}$  gm, or 1.00894 amu. It is a nucleon; it is basic in nuclear construction; and it exerts nuclear forces on other nucleons. The symbol of the neutron is  ${}_0\text{n}^1$ , or simply n.

c. The electron is the mobile negative charge in atoms, having an electric charge of  $-e$ ,  $4.80 \times 10^{-10}$  esu, and a mass of  $9 \times 10^{-28}$  gm (or 0.00055 amu). It exists in the outer structure of atoms, not in the nucleus, and is largely responsible for interatomic and molecular forces. When an electron is ejected from a nucleus in radioactive processes, it is called a  $\beta^-$  particle. The symbols are:

$${}_1\text{e}^0, {}_1\beta^0, \beta^-,$$

or simply e.

## 80. INTERACTION BETWEEN PARTICLES

a. These three elementary particles interact in several ways. Electrostatic forces exist between any two charges, according to the formula:

$$F = \frac{e_1 e_2}{r^2},$$

where  $e_1$  and  $e_2$  are the charges, and  $r$  is the separation. Therefore, protons exert electric forces on other protons and upon electrons.

b. Nuclear forces have already been described as having short range, being attractive but saturable, strong, charge independent, and spin dependent. These forces act between neutrons and protons and are roughly equal for (nn), (np), and (pp) combinations. The various properties of nuclear forces are partly accounted for by the meson theory, which will be mentioned later in this section.

c. The interactions of photons are manifold. Gamma rays of sufficient energy can create electron-positron pairs; that is, a gamma

ray may cease to exist as such and give rise to an electron and a positron in its stead. This is the pair production process. In other cases, a photon may excite a nucleus to a higher state, or it may excite or ionize an atom. All these photon reactions are basically electromagnetic interactions; the electric and magnetic fields of the photon exerting forces on the electric and magnetic fields of the particles involved.

## 81. CHART OF ELEMENTARY PARTICLES

a. This section presents a chart of most of the particles presently considered to be elementary. The term elementary particle means one which is not composed of other particles. Although a particle may convert itself into others, it is not composed of these others until its conversion, but is considered to be a basic entity.

b. This chart lists various properties of the elementary particles: mass, charge, decay if any, how obtained, how discovered, and their role in physics. A discussion of some of these properties will be made later. In addition to the elementary particles, certain basic aggregates of elementary particles will be listed which are of use and importance in physics.

## 82. BEHAVIOR OF PARTICLES

a. In figure 24, note that certain of these particles convert to others by radioactive decay. The free neutron decays to a proton, an electron ( $\beta$  particle) and a neutrino, with a half life of about 13 minutes. This may not be construed as implying that a neutron is composed of a proton, electron, and neutrino waiting to fly apart. A neutron bound into a nucleus will not in general decay. If it does so in certain circumstances, the nucleus is said to decay by  $\beta$  activity.

b. The positron is an interesting particle, demonstrated theoretically by Dirac's quantum mechanics in 1930, and found experimentally later. Dirac assumed that all space is pervaded by electrons in negative energy states, which are unobservable. An observable electron is in a positive energy state. Under some circumstances (e. g., under the influence of a high energy  $\gamma$ -ray) a negative energy electron may be kicked up into a positive energy state and observed as such. A "hole" in the negative energy state is then left, and this "hole" moves about as though it were a positive electron. Therefore, the positron's properties are nearly identical to those of the electron, except that it moves in the opposite direction in electric fields; that is, its charge is opposite.

c. When a positron meets an electron, it may combine, and the energy of the two electron masses is converted to electromagnetic radiation. On the Dirac picture, this annihilation process is a positive energy state electron making a transition to the negative energy hole, releasing energy. This transition requires the formation of two photons, in order to conserve spin in the process. The detailed theory is not necessary for the student now, and the further pertinent discussion of production of positron-electron pairs is given in paragraph 110.

d. The neutrino is another interesting particle whose existence was postulated on purely theoretical grounds. In the process of  $\beta$  decay of neutron and of nuclei, the energy of the  $\beta$  particle varies up to some definite maximum value. It was shown that the maximum value of energy was available in the nuclear transition which ejected the  $\beta$  particle, but that normally only a part of this energy was carried off by the  $\beta$  particle. Also, the spin angular momentum of the original nucleus differed by one-half unit from the sum of the spins of the resultant particles. These two discrepancies were explained by using an additional particle, the neutrino. The neutrino and  $\beta^-$  particle are emitted together. The neutrino had to have essentially no mass, no charge, but spin one half. Experiments performed to find any direct interaction of the neutrino have been so far unsuccessful, but this elusive particle is observed indirectly.  $\beta$ -active nuclei are observed to recoil with momenta which indicate the existence of the neutrino.

e. The alpha particle, deuteron, and triton are aggregates of protons and neutrons which tend to stick together during nuclear reactions. Thus  $\alpha$  particles are emitted in heavy element radioactivity. Deuterons are emitted and absorbed in certain reactions. Tritons, or  ${}_1\text{H}^3$  nuclei, are radioactive, and decay to  ${}_2\text{He}^3$  with a 12-year half life. However, cosmic ray neutrons are continually forming tritium from deuterium, so that a minute amount exists in nature.

f. A gamma ray is included as an elementary particle because these photons behave like particles in their interactions. A theory similar to the meson theory has been used to describe the interaction of photons with matter, and to explain the electrostatic field forces. Under this theory, photons are exchanged between electric charges, and the electric forces result. Normally these photons are unobservable, unless energy is supplied to accelerate a charge, in which case observable radiation is emitted. These theories of exchange forces and electromagnetic field quantization need not be considered as important for this course, only as interesting supplementary information. Further reading along these lines for interested students might be had in Glasstone, Sourcebook on Atomic Energy, Second Edition,



Particle & Symbol	Charge	Mass	Remarks on Discovery, How Obtained, Purpose
proton $1p^1$	$+e$	1.00758 amu or 1840 me or $1.67 \times 10^{-24}$ g 931 Mev	Rutherford discovered proton by ( $\alpha$ , p) reaction in nitrogen. Hydrogen nucleus. Basic charged nuclear particle.
neutron $0n^1$	0	1.00894 amu or 1840 me or $1.67 \times 10^{-24}$ g or 931 Mev	Chadwick discovered neutron by ( $\alpha$ , n) reaction on beryllium. Basic neutral nuclear particle. Free neutron decays: $0n^1 \rightarrow 1p^1 + 1e^0 + 0\nu^0$ Half life 13 min.
electron $1e^0$ or $\beta^-$	$-e$	.00055 amu 1 me or $9.1 \times 10^{-24}$ g	Electrons are the orbital structure in atoms; carriers of electricity.
positron $+1e^0$ or $\beta^+$	$+e$	.00055 amu 1 me or $9.1 \times 10^{-28}$ g	Anderson in 1933 discovered positron in cosmic rays. Predicted by Dirac theory of quantum mechanics of electron. Recombines with an electron, forming 2 $\gamma$ 's.
neutrino $0\nu^0$	0	< 5 Kev	Carries off excess energy, momentum, and spin in $\beta$ decay. Difficult to detect directly.

Particle & Symbol	Charge	Mass	Remarks on Discovery, How Obtained, Purpose
gamma ray $\gamma^0$	0	0	Electromagnetic field quanta, photons with $E = h\nu$ .
alpha particle ${}_{2}^{4}\text{He}$	$+2e$	4.0028 amu	Combination of $2p + 2n$ into a ${}_{2}^{4}\text{He}$ nucleus. A radioactive decay particle.
deuteron ${}_{1}^{2}\text{H}$	$+e$	2.01416 amu	An ${}_{1}^{2}\text{H}$ nucleus, used in many nuclear particle reactions.
triton ${}_{1}^{3}\text{H}$	$+e$	3.01647 amu	An ${}_{1}^{3}\text{H}$ nucleus, used in nuclear reactions. It decays with half life of 12 years. ${}_{1}^{3}\text{H} \rightarrow {}_{2}^{3}\text{He} + \beta^{-} + \nu$

$+me$  = mass of electron

Figure 24. Table of Elementary Particles

Sec. 12.31-12.36, and in Pollard and Davidson, Applied Nuclear Physics, Second Edition, chapter 12.

### 83. WAVE-PARTICLE DUALISM

a. One further concept regarding particles will be useful in thinking about nuclear physics. It has been mentioned that photons travel as electromagnetic waves but are absorbed and emitted as though they were particles. In other words, radiation may be regarded as having a dual wave-particle nature.

b. This dualism of the wave and particle functions of radiation led Louis de Broglie to suggest that a similar dualism might exist for material particles. He showed that a particle of mass  $m$  moving with a velocity  $v$  should be associated with waves of length  $\lambda$ , given by

$$\lambda = \frac{h}{mv} \quad (h = \text{Planck's constant})$$

$mv$  is the momentum of the particle, which is often represented by the symbol  $p$ .

c. Calculations show that for anything except the smallest particles, the wavelengths of the matter waves, as they are often called, are extremely small. No means is available at present to measure such wavelengths.

d. Experimental results with small particles showed de Broglie's assumption to be correct. A beam of electrons actually was diffracted by a diffracting screen exactly as if the electrons were photons. Thus, the wave-particle duality may be considered to be a fundamental property of nature.

e. In view of this property, one may wonder if there is any point in making a distinction between a wave and a particle. In a sense, such a distinction is meaningless, since everything has a wave character or a particle character, depending on the circumstances.

f. Particles or waves are generally so classified because of their familiar properties. Neutrons or molecules are referred to as particles because their familiar properties (mass, volume, etc.) are generally associated with particles. Light or gamma rays are referred to as waves because their familiar properties are generally associated with waves.

## SECTION III. BINDING ENERGY

### 84. GENERAL

In this section, the principles of nuclear binding energy will be discussed. Because all presently known methods of obtaining nuclear energy depend upon changes in binding energies, this subject is basic to an understanding of all atomic energy devices. The concept, methods of calculating binding energy, and methods of utilizing it will be discussed. For the sake of completeness and interest, the methods of measuring and computing atomic masses are also given.

### 85. DEFINITION

Binding energy is that energy which must be supplied to a group of particles to free them of each other's forces. This means that for a nucleus, the total binding energy is the energy needed to separate all the nuclear particles. Whenever two particles are held together by forces of any kind, there is some binding energy. For example, an electron in the hydrogen ground state orbit requires 13.5 ev of energy to pull it entirely away from the proton. When an electron is pulled into its orbit from a long distance ( $n = \infty$ ) to the ground state ( $n = 1$ ), a 13.5-ev photon is emitted. The atomic system is more stable in its  $n = 1$  state; and the excess energy possessed by the electron when it was outside must be eliminated, in this case, by electromagnetic radiation. The energy lost in forming a bound state of electron and nucleus is the binding energy; and if a 13.5-ev photon enters a hydrogen atom, it may free the electron from its bound state.

### 86. MASS DEFECT

a. The nucleus of an atom contains neutrons and protons which are bound together by much stronger forces than the electric forces holding electrons in the atom. This means that more energy must be provided to pull the nucleus apart; consequently, the binding energy of the nucleus is much greater than that of orbital electrons.

b. According to the conservation law of mass and energy,  $E = mc^2$ , whenever energy is created, mass is lost. Now if it takes work to separate the nucleons from a nucleus, then some energy must have been given up in the process of binding these nucleons together. This amount of energy created in the binding process must therefore result

in a loss of mass in the nuclear system. The loss of mass, called mass defect, corresponds to the binding energy. If  $B.E.$  is the binding energy of a nuclear system, then the mass defect  $\Delta M$  is given by the equation.

$$B.E. = (\Delta M) c^2.$$

## 87. CALCULATION OF BINDING ENERGY

a To see how this binding energy concept enters into the nuclear picture given in paragraph 73, consider the process of forming a deuteron from a neutron and a proton. The mass of a proton is 1.00758 amu, and that of a neutron is 1.00894 amu. Thus, the total mass of the constituent particles of a deuteron is 2.01652 amu. The measured mass of the deuteron is 2.01416 amu, which is 0.00236 amu lighter than the sum of its parts. In other words,

$$M_p + M_n = M_d + \Delta M,$$

where  $M_p$ ,  $M_n$ , and  $M_d$  are proton, neutron, and deuteron masses respectively, and  $\Delta M$  is the mass defect. Converted to energy units, 0.00236 amu is 2.2 Mev (multiply by 931 Mev/amu), and this energy is the measured binding energy of the deuteron. If 2.2 Mev is supplied to a deuteron, the neutron and proton may be separated. In this same way, mass defects and binding energy may be calculated for all nuclei whose masses are known accurately enough.

b In Appendix IV, Table of Atomic Masses, a fairly complete list of common isotopes is given, with the atomic mass of each as determined by experiment. Notice that the nuclear masses are not given, but the total atomic masses, including electrons. If the mass of a nucleus is desired, the mass of  $Z$  electrons at 0.00055 amu per electron is subtracted from the atomic mass. However, to calculate binding energies, it is not necessary to use the nuclear mass, since larger atoms may be considered to be made up of hydrogen atoms ( ${}_1H^1$ ) and neutrons. Then, the electrons are added to the nuclear particle masses on both sides of the equation for mass defect. For example, calculation of the binding energy of  ${}_2He^4$  is made as follows: First add 2 hydrogen atom masses and 2 neutron masses. The hydrogen atom masses contain one electron mass each.

From the table,

$$M_1H^1 = 1.00813 : 2 MH = 2.01626 \text{ amu}$$

$$Mn = 1.00894 : \underline{2 Mn = 2.01788 \text{ amu}}$$

$$\text{Total } M = 4.03414 \text{ amu;}$$

this figure includes two electron masses.

Also from the table, He-4 atomic mass = 4.00390. This figure also includes two electron masses. The nuclear mass in an He-4 atom is thus  $4.00390 - 2 me$  and the nuclear mass of 2 protons and 2 neutrons is  $4.03414 - 2 me$ . Therefore, the mass defect of  ${}_2\text{He}^4$  nucleus is given by:

$$\begin{aligned} \Delta M &= (4.03414 - 2) - (4.00390 - 2) \\ &= (4.03414 - 4.00390) = 0.03024 \text{ amu.} \end{aligned}$$

The student should clearly understand how he may calculate nuclear mass defects using the masses of neutral atoms as given in Appendix IV, Table of Atomic Masses. He should recognize that the electron masses balance out of the computation if neutral atomic masses are used throughout the problem. The total energy of the  ${}_2\text{He}^4$  nucleus is then given by:

$$\text{B. E.} = \left( 931 \frac{\text{Mev}}{\text{amu}} \right) (0.03024 \text{ amu}) = 28.1 \text{ Mev.}$$

c. The student should calculate the binding energy of  ${}_8\text{O}^{16}$  nuclei by the method described. For practice, calculate also the binding energy of  ${}_6\text{C}^{14}$  and  ${}_7\text{N}^{14}$  nuclei.

## 88. SIGMA

a. The total binding energy is the energy needed to totally disrupt the nucleus. A more useful concept for this course is that of binding energy per particle,  $\Sigma$ . This quantity is defined by:

$$\Sigma = \frac{\text{Total B. E.}}{A} \text{ in Mev.}$$

Therefore, 
$$\Sigma = \frac{(\Delta M) c^2}{A} \text{ in Mev}$$

$$= \frac{\Delta M}{A} \times 931, \text{ where } \Delta M \text{ is in amu.}$$

Also, according to paragraph 87, the mass defect is:

$$\Delta M = [1.00813 (Z) + 1.00894 (A - Z)] - M_{\text{atom}}$$

These equations are sufficient to calculate  $\Sigma$  from the isotopic atomic mass table.

b. The binding energy per particle is the average energy required to free a particle from the nucleus. It is also the apparent loss of energy due to the binding of one of the nucleons.  $\Sigma$  converted to mass is the apparent average loss of mass of a nucleon when it is bound into a nucleus. Thus,

$$\frac{\Sigma}{931} = \text{individual mass loss per nucleon.}$$

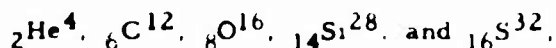
This can be said another way. When a proton or neutron is bound into a nucleus, it appears to have less mass than when it is free.

c. The  $\Sigma$  versus  $A$  curve plotted in figure 25 shows several significant features

(1) The elements in the middle of the curve have the highest binding energy per particle, and therefore are the most stable.

(2) The largest binding energy per particle is about 8.7 Mev.

(3) Certain nuclei show extra stability as compared with their neighbors. This extra stability is evidenced by:



which are nuclei with alpha particle multiples.

(4) The change in binding energy per particle in a transmutation of a heavy nucleus into lighter nuclei is relatively small. The change in binding energy per particle in a transmutation involving fusing light nuclei into heavier is large.

## 89. FISSION AND FUSION

a. These last considerations show how the energy is released in the fission process and in the fusion process. When a nucleus fissions, it splits into two roughly equally sized smaller nuclei. The binding energy per particle increases in this process, and this change of energy is released as kinetic energy of the fission fragments. In



Figure 25.  $\Sigma$  Versus  $A$  Curve

other words, mass is lost in the fission process from the change in binding energy. No nucleons are destroyed, but their tighter binding releases energy. For example,

${}_{92}\text{U}^{235}$  has  $\Sigma = 7.5$  Mev/particle.

It may fission into two middle range elements, with  $\Sigma$  about 8.3 Mev/particle. Thus 0.8 Mev/particle is released from the process of binding these nucleons more tightly. Including the neutron which caused fission, there are 236 particles, so the total energy released is  $(236)(0.8) = 189$  Mev.

b. In a fusion reaction, several light nuclei, say  ${}_1\text{D}^2$  and  ${}_1\text{T}^3$  fuse together nuclearly to make a heavier, more tightly-bound nucleus. Thus again, the binding energy per particle increases, and this energy is released. The binding energy for  ${}_1\text{D}^2$  is 2.2 Mev and for  ${}_1\text{T}^3$  is 8.4 Mev. Under suitable conditions,  ${}_1\text{D}^2$  and  ${}_1\text{T}^3$  can be made to fuse into  ${}_2\text{He}^4$  and an unbound neutron. The binding energy, for  ${}_2\text{He}^4$  is 28.2 Mev. Thus, the binding energy has increased  $28.2 - (2.2 + 8.4) = 17.6$  Mev per fusion.

## 90. CALCULATION OF ENERGY RELEASE

a. Another related approach to the release of energy in fission and fusion may be made. When nucleons bind together, energy is



released. The amount of energy is the binding energy; and if this were supplied to the bound nucleus, it could separate it into its components. The way to calculate this binding energy for a given nucleus is to add the total constituent particle mass and compare it with the bound nucleus mass. The bound nucleus weighs less than the sum of its parts. This mass defect times  $c^2$  equals the binding energy.

b. Now notice that each nucleon appears to have lost mass in being bound. The average loss of mass per nucleon times  $c^2$  equals the binding energy per particle,  $\Sigma$ . Therefore, the most tightly-bound nuclei have nucleons whose average mass is least. Figure 26 plots a curve of average mass per nucleon. From this curve, one sees that per nucleon involved, the mass loss is greater for fusion than for fission. In both fission and fusion, the binding becomes tighter and the average mass for a particle in the nucleus decreases. This mass loss appears as a creation of energy. The average mass of a nucleon bound into a nucleus is given by the equation:

$$M_{av} = \frac{M}{A}$$

$$\text{For U-235} \quad M_{av} = \frac{235.1133}{235} = 1.00048$$

$$\text{For Xe-132} \quad M_{av} = \frac{131.946}{132} = 0.99959$$

$$\text{For Mo-100, } M_{av} = \frac{99.945}{100} = 0.99945$$

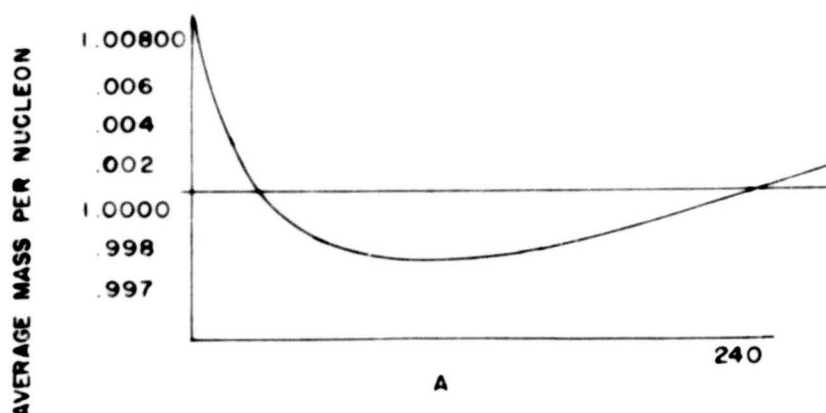


Figure 26. Average Mass Per Nucleon

Thus, in a hypothetical fission process where U-235 fissions to Xe-132 and Mo-100, the total energy released is equal to the total change in mass, which is equal to the sum of:

$$(100) (1.00048 - 0.99945) (931)$$

from conversion of 100 nucleons to a lower average mass and

$$(132) (1.00048 - 0.99959) (931)$$

from conversion of 132 nucleons to a lower average mass. The total energy released is thus:

$$(100) (931) (0.00103) + (132) (931) (0.00089) = 205 \text{ Mev}$$

for this particular fission.

c. The student should recognize that binding energy causes the apparent loss of mass of nuclear particles, and that the approaches made to binding energy release in fission and fusion in this paragraph and in paragraph 89 are really the same.

## 91. SUMMARY

From this chapter, the student should have learned what binding energy is and from what effect it arises. He should know the way in which energy is released in fission and fusion of nuclei, as well as what these processes are. He should be able to calculate total binding energies,  $\Sigma$ , mass defects, average bound nucleon mass, and the energy released in a given nuclear process where binding energy changes.

## 92. PROBLEMS

a. Calculate the total binding energy of the following nuclei:

$$(1) {}_6\text{C}^{12}$$

$$(2) {}_{82}\text{Pb}^{207}$$

$$(3) {}_{92}\text{U}^{235}$$

b. Calculate the binding energy per particle for each of the nuclei in problem a.

## CHAPTER 5

### RADIATION

#### SECTION I. RADIOACTIVITY

##### 93. INTRODUCTION

Radioactivity is one of the more popular aspects of nuclear physics and is of rapidly growing importance in many fields. A knowledge of radioactivity is especially necessary for anyone working with atomic weapons. Some materials within these weapons are radioactive, as are the byproducts of an atomic explosion. An understanding of the effects of radioactivity on materials and humans is becoming vital to everyone in the atomic age.

##### 94. HISTORY

Radioactivity was first discovered by Becquerel in 1896, quite by accident. He had intended to study the fluorescence of certain rocks after they were exposed to sunlight. Fortunately, the sun failed to shine in Paris for a few days, and the rocks, containing uranium, were left in a drawer beside the photographic plates. When developed, the plates showed a dark autoradiograph of the rocks. Evidently the rocks were emitting some kind of radiation of their own which was not dependent upon the sun. In 1898, Marie Curie named this process radioactivity.

##### 95. CHARACTERISTICS OF NATURAL RADIOACTIVITY

a. Not long after Becquerel's discovery of the radioactivity of uranium, similar discoveries were made with a number of other heavy elements. Further experiments produced information about the nature of these mysterious radiations, the findings were startling at that time. The outstanding effects observed about radioactive elements include the following:

(1) There are three types of radiation emitted, and these differ greatly in their penetrating powers in various materials. See figure 27. These basic radiations are symbolized by three Greek

letters, alpha ( $\alpha$ ), beta ( $\beta$ ), and gamma ( $\gamma$ ).

(2) Any naturally radioactive element will emit one, or more, of these three basic radiations.

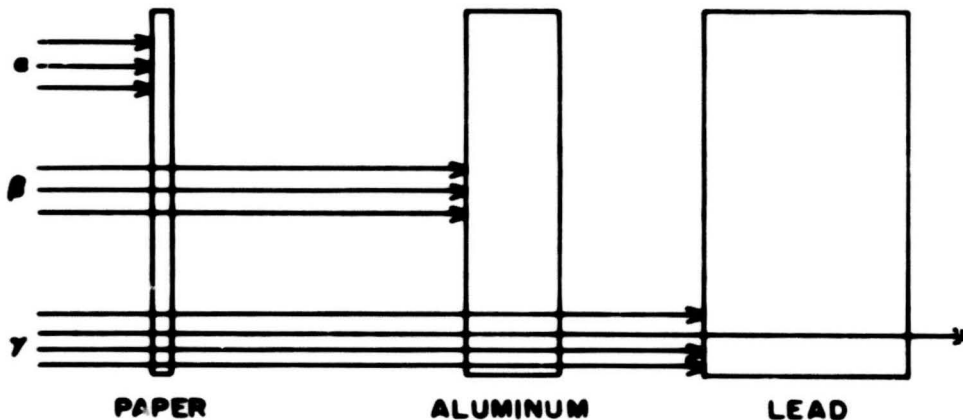
(3) The radiations are emitted continually and at a rate that is unaffected by temperature, pressure, or by the presence of other elements that may be chemically combined with a radioactive element.

(4) Radioactive elements are continually creating small quantities of other elements, some of which may also be radioactive. For example, radium generates helium and radon (both gases) as byproducts. Radon is also radioactive.

(5) Radioactive materials are constantly emitting energy and hence, are generally at higher temperatures than their surroundings. They are, therefore, sources of heat.

#### NOTE

Although these properties of radioactive elements seem peculiar at first, they become reasonable when more details have been given about the nature of radioactivity.



**Figure 27. Demonstration of the Relative Penetrating Power of Three Nuclear Radiations**

b. One of the most enlightening means of separating the three basic radiations is to pass a mixed beam of these radiations through a magnetic field. See figure 28. In doing this, the beam splits into three components. One component passes through the magnetic field without deflection, which indicates that it is uncharged. The other two components are deflected in opposite directions, indicating that one is positively charged and the other negatively charged. The positive radiation is called alpha ( $\alpha$ ), the negative radiation is called beta ( $\beta$ ), and the neutral radiation is called gamma ( $\gamma$ ).

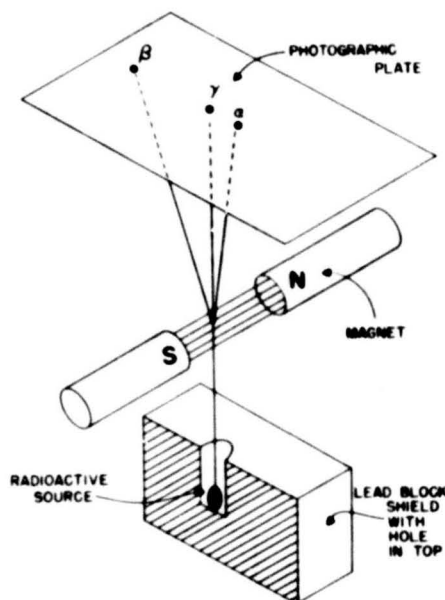


Figure 28. Deflection of Radiations in a Magnetic Field

c. The other unusual properties of radioactive elements arise primarily because these radiations originate within the nucleus. This explains why radioactivity is independent of temperature and other atoms that might be chemically combined with a radioactive atom. Temperature and chemical reactions have no appreciable effect upon an atom's nucleus.

d. The peculiar forces that are found to exist within a nucleus are such that many nuclei are unstable. Consequently they tend to change to a different form or structure in which they are more stable. The stability of a nucleus is closely related to the energy of the individual nucleons within the nucleus. The more energy possessed by the nucleons, the greater will be the chances that part of the nucleus

will break off and escape, or that some arrangement will take place resulting in the emission of energy. In either case, the end product of radioactivity is a nucleus with less energy and therefore more stability.

e. When part of the structural material of a nucleus is emitted, the remaining material will form a new nucleus with either different Z, different A, or both. The main criterion for this to occur is that the nucleons of the "daughter" nucleus must have less energy than those of the "parent" nucleus. Finally, energy given up in the radioactive process heats up the source material and its container.

## 96. ALPHA DECAY

a. It has already been noted that alpha radiations are positively charged and have relatively short ranges. The nature of the alpha particle was determined by experimentation. Alpha particles from radon gas were collected in an evacuated bottle, and later analysis showed the contents of the bottle to be helium gas. Other experiments which measured the charge and mass of alpha particles supported this observation; as a result, alpha particles are known today to be helium-4 nuclei, composed of 2 protons and 2 neutrons (symbol  ${}^4_2\text{He}$ ).

b. Due to the large positive charge on an alpha particle (+2), it attracts electrons strongly. Alpha particles passing through a material tend to strip off electrons from atoms within the material. This process is called ionization, and atoms that have had electrons removed (or added) are called ions. The alpha particles are generally traveling fast enough so that the electrons stripped from surrounding matter are not captured by the alpha particle itself until it has slowed down considerably. The stripped electrons and positively charged particles remain on the path traced by alpha particles. Alphas are the most heavily ionizing radiation found in natural radioactivity and are capable of producing as many as 70,000 ion pairs in 1 centimeter of travel in air. An ion pair consists of 1 positively charged entity and 1 negatively charged entity. Upon slowing down and stopping, the alpha will gain two orbital electrons and become a stable  ${}^4_2\text{He}$  atom. More details on ionization by alpha particles are given in section II.

c. One important characteristic of alphas is their discrete energies, which means that for any alpha-emitting material, emission takes place at only certain definite energies. In fact, many isotopes emit alphas of only one energy. For example, alphas from U-238 all have 4.2 Mev, while U-235 emits alphas with 4.39 and 4.56 Mev. The discrete alpha energies are in harmony with the observations that nuclei can exist only in certain allowed energy states. Therefore, any

structural change should involve a discrete energy.

d. Since an alpha particle removes 2 protons and 2 neutrons from the parent material, the remaining structure forms a new nucleus with  $Z$  decreased by 2 and  $A$  decreased by 4. For example,  ${}_{92}\text{U}^{238}$  decays by alpha emission to  ${}_{90}\text{Th}^{234}$ , and similarly  ${}_{88}\text{Ra}^{226}$  decays to  ${}_{86}\text{Rn}^{222}$ .

e. Alpha decay has very important consequences in determining nuclear structure. Probably the best explanation of alpha decay is simply: as a nucleus gets more and more positively charged, a point is reached where the repulsive strength of the coulombic forces is comparable with the cohesive nuclear forces. This is found to occur in atoms whose atomic number is greater than 82. This actually oversimplifies alpha emission because calculations show that on the average an alpha group is bound to heavy atoms with an energy of about 25 Mev. However, alpha particles seldom have energies greater than 10 Mev, and it would seem that alpha emission should never occur. The diagram in figure 29 depicts a typical plot of the potential energy that an alpha particle would experience in the space inside and around a nucleus. As a positively charged particle approaches a nucleus, the repelling coulombic force increases sharply as designated by the curved slopes in figure 29. The greater the repelling force on the particle, the greater will be its potential energy. Once the positive particle gets within the nucleus, however, the repelling force ceases and the strong nuclear attraction takes over. This results in a sharp drop of about 25 Mev in the potential energy of the alpha particle. Considering, now, the reverse case, the strong nuclear attraction gives rise to a potential barrier for alpha emission, since an alpha should have 25 Mev in order to escape. However, the fact that alphas do escape with 4 to 10 Mev needs further explanation.

f. It should be no great surprise that ideas about nature, which are based on observations of samples of materials containing many atoms, do not apply exactly to the events taking place within a single atom. As a result, the classical notions of physics have been expanded greatly and incorporated into broader theories which have explained, in part, the peculiarities of atomic and nuclear physics. The theory upon which much of our understanding of the atom is based is called wave mechanics, when applied to alpha decay, it predicts that 4 to 10 Mev alpha particles can actually tunnel through the 25-Mev potential barrier set up by a nucleus (see paragraph 144). Although this barrier greatly reduces the rate at which alpha particles escape, their chances of escape are finite, and normal alpha decay results.

g. Another fact that is difficult to explain is why a nucleus does

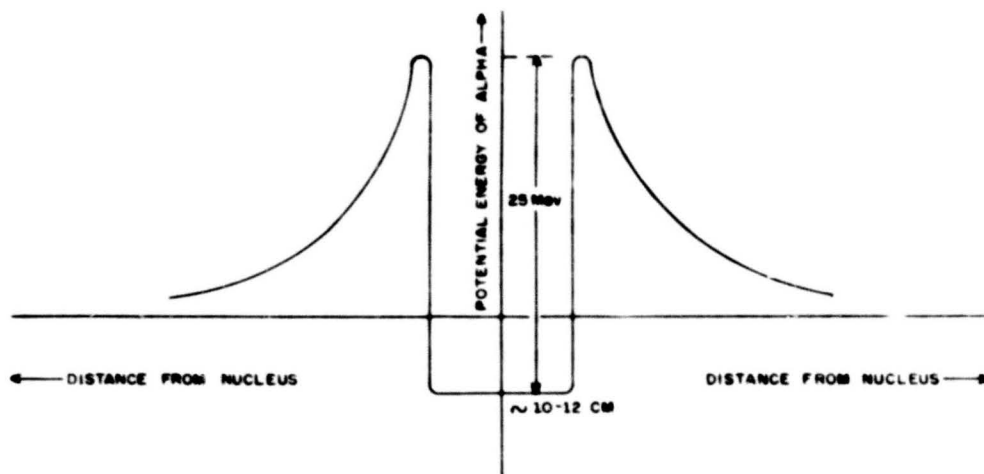


Figure 29. Plot of the Potential Energy of an Alpha With Range in the Vicinity of a Nucleus

not emit a proton alone, or a group of protons and neutrons larger than the alpha group. There is no really convincing argument to explain this except to say that it just happens this way. It develops that the energy needed to break up an alpha into its four constituent particles is 28.2 Mev, while the binding energy of a  ${}^3_1\text{H}$  nucleus is only 8.4 Mev. Therefore, it would take 17.8 Mev to remove a proton from an alpha particle. This makes single proton emission very much less probable than alpha emission.

h. The nature of nuclear forces is such that an alpha particle and multiples of the alpha group (such as  ${}^{12}_6\text{C}$  and  ${}^{16}_8\text{O}$ ) are very stable structures. This does not exclude the possibility that a larger particle containing two or more alphas might be emitted. This practically never occurs because the huge potential barrier presented to a larger particle makes tunneling virtually impossible.

## 97. BETA DECAY

a. The reader will recall that beta radiation is characterized by a negative charge and a large charge-to-mass ratio (as compared to alphas). Further analysis shows that beta particles have the same charge and mass as electrons, and this has led to the definite



identification of these particles as electrons. They are very special electrons, however, because they come from the nucleus and have very high energies. To distinguish them by source, they are called beta particles (symbol  ${}_{-1}\beta^0$  or  $\beta^-$ ) rather than electrons.

b. The emission of beta particles from a nucleus immediately brings up the following question: "How can electrons come from a nucleus made up of protons and neutrons, but no electrons?" Beta decay arises because under certain circumstances the nucleus can force a neutron to decompose into a proton and an electron. The outward symptom of these circumstances is an n/p ratio which lies above the stability region. See figure 23.

c. Since beta particles have a negative charge, they are able to ionize the atoms in the media through which they pass. However, due to the difference in charge and speed, the ionizing ability of beta particles is approximately one hundredth that of an alpha particle. In order to produce an ionizing event, a particle must give up enough energy to an atom to remove an electron. Therefore, the more ionizing a particle is, the faster it will give up its energy and the shorter will be its range. The beta particle travels faster than the alpha particle and has less charge, therefore, it cannot give up its energy as rapidly and that is why the range for beta particles is longer and the ionizing power less than for alpha particles.

d. A more striking difference between alpha and beta radioactivity is their emission energies. Recall that alpha particles are emitted with certain definite energies only. Beta particles, on the other hand, are emitted over a wide, continuous range of energies. This is demonstrated in figure 30, which shows a typical distribution of beta energies. The height of the curve at any energy level gives the percentage of beta particles which have this particular energy.

e. One important observation to be made from this curve is that no particles have an energy above that labeled  $E_{\max}$ . It is also found that the energy difference between the nucleus before beta decay and the new nucleus after beta decay is equal to  $E_{\max}$ . This actually is a very disturbing fact because it means that the great majority of beta particles, whose energy is less than  $E_{\max}$ , have less energy than their parent nuclei gave up in emitting them. Here is a case where energy is apparently lost.

f. At first, it was thought that gamma rays might have been emitted in addition to the betas to account for the energy discrepancies. However, the gamma rays have never been detected. This has led scientists to make a bold postulate as to the existence of another

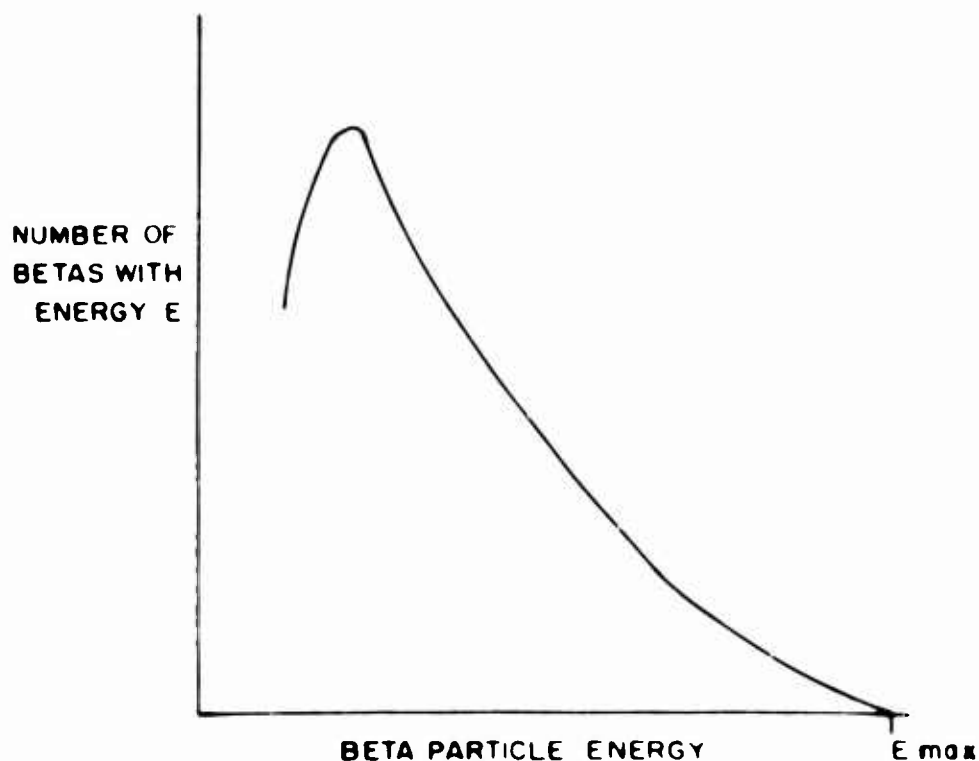
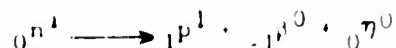


Figure 30. Energy Distribution (or Spectrum) of Beta Particles From Typical Source

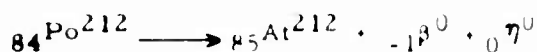
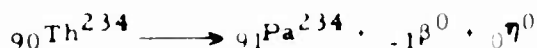
particle called a neutrino (symbol  $\bar{\nu}^0$  pronounced eta). A neutrino is thought to be emitted in addition to a beta particle in such a way that the energy of the beta and the energy of the neutrino add up to  $E_{\max}$ . Therefore, beta decay does not violate the idea that all subatomic changes involve discrete energies. The discrete energy in the case of beta decay is  $E_{\max}$ .

g. Studies of beta decay have uncovered discrepancies other than energy that make the neutrino hypothesis seem even more necessary. However, the physical properties of the neutrino are such that it is extremely difficult to observe. This is because the neutrino is postulated to be a chargeless ( $Z = 0$ ) particle with almost zero mass. Recent experiments indicate that the neutrino does, in fact, exist.

h. The complete reaction for beta decay is



Note that beta decay charges the parent nucleus by increasing its  $Z$  by one ( $A$  remaining constant). The following are actual examples of beta emissions and the new elements which result:



1. Some beta emitters have several upper limit energies corresponding to different energy states of the parent, just as was found with alpha decay. For example,  ${}_{90}\text{Th}^{234}$ , mentioned above, emits betas with two upper limit energies, 0.20 Mev and 0.11 Mev, while  ${}_{84}\text{Po}^{212}$  emits betas with a single  $E_{\text{max}}$  of 2.25 Mev.

## 98. ELECTRON CAPTURE

a. There are special instances where another type of decay takes place. This occurs primarily when the  $n/p$  ratio is below the stability region. See figure 23. A proton absorbs an atomic electron, a process called electron capture or K capture.<sup>1</sup> The complete reaction for electron capture is:



where the neutrino is again necessary to avoid conflicts with the law of energy conservation. Note that electron capture produces a new nucleus with  $Z$  decreased by one.

b. Electron capture is always accompanied by the emission of X-rays, which results from another orbital electron falling into the place vacated by the captured electron. The energy lost by the electron is emitted as a photon whose frequency is in the X-ray range. However, the frequency of the photon is characteristic of an electron falling to the K shell of the product element rather than the original element.

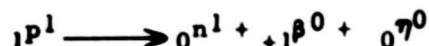
## 99. POSITRON EMISSION

a. The same products as are produced by K shell capture are also produced by the emission of a particle called a positron, which

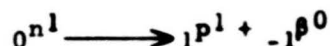
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<sup>1</sup> Called K shell capture since the electron is captured from the innermost (K) shell of the atom.

has the mass of an electron, but a positive charge (symbol  ${}_{+1}\beta^0$  or  $\beta^+$ ). This reaction occurs when a proton is transformed by the influence of the nucleus into a positron and a neutron. The reaction is:



Note that this reaction does not occur in nature for free protons. The transformation occurs only under the influence of all the nucleons in the nucleus. A symptom which indicates that such a transformation might occur is that the n/p ratio is below the stable region. See figure 23. It should be mentioned that the reaction:



does occur for free neutrons in addition to the transformation of neutrons inside the nucleus in  $\beta^-$  decay. The half life for free neutron decay is about 13 minutes. The transformations of the neutron and protons taking place in radioactivity are induced by forces present in the nucleus and under special conditions. Symptoms of these conditions are usually that the n/p ratios do not lie in the stability region.

b. Positron emission and K capture are relatively rare in natural radioactivity and are mentioned mainly for completeness. However, they do have interesting consequences to nuclear physics in general, and the curious reader is referred to advanced texts.

## 100. GAMMA RADIOACTIVITY

a. Gamma radiation is by far the most penetrating form of radioactivity and is different from alpha and beta radiations in that it is electromagnetic in nature. When a nucleus emits energy without a change in atomic mass or atomic number, the energy appears in the form of electromagnetic waves or photons. Since gamma photons are uncharged, they are unaffected by magnetic fields. Their ionizing ability is very much less than that of alpha or beta radiation, which explains their long range. Gamma rays do ionize by special processes which will be described in the next section.

b. The emission of gamma rays is accompanied by the change in energy state of the parent nucleus, and therefore gamma rays are always emitted with discrete energies. Frequently gamma rays are emitted in conjunction with beta or alpha particles. For example, in 94.3 percent of the atoms of  ${}_{88}\text{Ra}^{226}$  decaying to  ${}_{86}\text{Rn}^{222}$  by alpha emission, 4.79 Mev alpha particles occur alone. In the remaining 5.7 percent of the decays, 4.61-Mev alpha particles are followed by

0.18-Mev gamma rays. In nearly all polonium-210 alpha decays, however, 5.3-Mev alpha particles are emitted with no  $\gamma$  fission. In less than 0.001 percent of the cases, a 4.5-Mev alpha particle and an 0.8-Mev  $\gamma$  ray result. See figure 31.

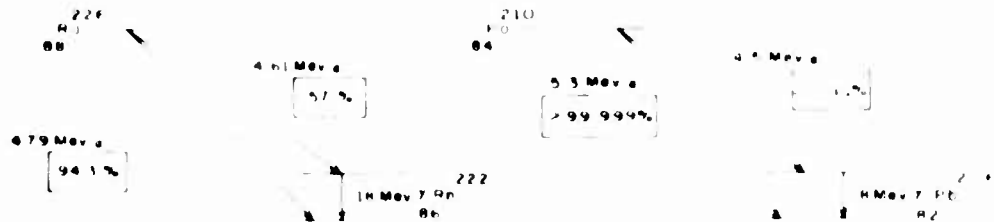


Figure 31. Energy Level Diagrams for Alpha Decay of Ra-226 and Po-210

#### 101. NUCLEAR STABILITY AND RADIOACTIVITY

a. As previously noted, radioactivity is a result of the instability of nuclei. Because today's knowledge of nuclear forces is limited, science is unable to completely explain why some nuclei are more stable than others. However, certain rules have been observed to be followed by stable isotopes as to their relative numbers of neutrons and protons.

b. If the ratio of neutrons to protons is plotted against atomic number, a smooth curve results which lies close to the line representing a neutron to proton ratio of 1 and increases gradually to 1.6. See figure 23. This indicates that the forces between neutrons and protons are slightly stronger than those between neutrons alone or protons alone. These ideas fit with the previously noted facts about the stability of alpha particles and multiples of the alpha group, whose neutron-to-proton ratios are exactly one.

c. The gradual increase in the proportion of neutrons in going to heavier elements is attributed to the increasing coulombic repulsion from the protons in heavy nuclei. Were it not for the electrical charge of the protons, it is expected that all nuclei would have a neutron-to-proton ratio of nearly one. It is apparent, however, that additional neutrons are necessary for heavy nuclei to overcome coulombic repulsion. It is expected then that any nucleus whose neutron-to-proton ratio lies well off the stability curve will be radioactive and

will emit a form of radiation that will place the product nucleus closer to the curve.

## 102. ARTIFICIAL RADIOACTIVITY

a. If stable nuclei on the curve in figure 23 are bombarded with external radiations of alpha and beta particles, protons, neutrons, etc., these particles are frequently captured and new isotopes (and elements) are produced. Many isotopes produced in this way have had their  $n/p$  ratio altered enough to become radioactive and are often capable of other forms of radioactivity than the alpha, beta, and gamma radiations emitted by natural radioactive isotopes. For example, alpha particles on  ${}_{13}\text{Al}^{27}$  produce  ${}_{15}\text{P}^{31}$  which decays rapidly to  ${}_{15}\text{P}^{30}$  plus a neutron. Similarly, alpha particles on  ${}_{7}\text{N}^{14}$  yield  ${}_{8}\text{O}^{17}$  and a proton. This latter reaction is very interesting historically because it was the first man-controlled "transmutation" of one element into another. Since then, however, hundreds of other induced transmutations have been discovered.

b. If the  $n/p$  ratio is too large for stability, the most likely reactions are  $\beta^-$  decay or possibly neutron emission. If the  $n/p$  ratio is too small, however,  $\beta^+$  decay, electron capture, or proton emission are possible.

## 103. DECAY LAWS

a. In paragraph 95, it was noted that no chemical or physical means could alter the rates at which a radioactive element decayed. Given a large sample of radioactive atoms, it is possible to predict how many atoms will decay in a given instant, but it is impossible to predict which atoms will decay. For this reason, radioactivity is called a random process.<sup>1</sup> The sample must consist of at least several millions of atoms or the argument that follows will not hold.

b. It is found that the number of atoms undergoing decay per second is proportional to the number of atoms present. Therefore, the ratio of the number of atoms decaying in a unit time to the total number of atoms present is a constant, called the decay constant,  $\lambda$ .  $\lambda$  can be interpreted as the probability that a given number of atoms will decay in a unit time and has units of  $\text{time}^{-1}$ .  $\lambda$  varies considerably from one material to another and can be found written with units varying from  $\text{seconds}^{-1}$  to  $\text{years}^{-1}$ .

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<sup>1</sup> A more familiar random process is encountered in flipping a coin. A large number of flips should produce 50 percent heads and 50 percent tails, but we are unable to predict which event will occur in a particular toss of the coin.

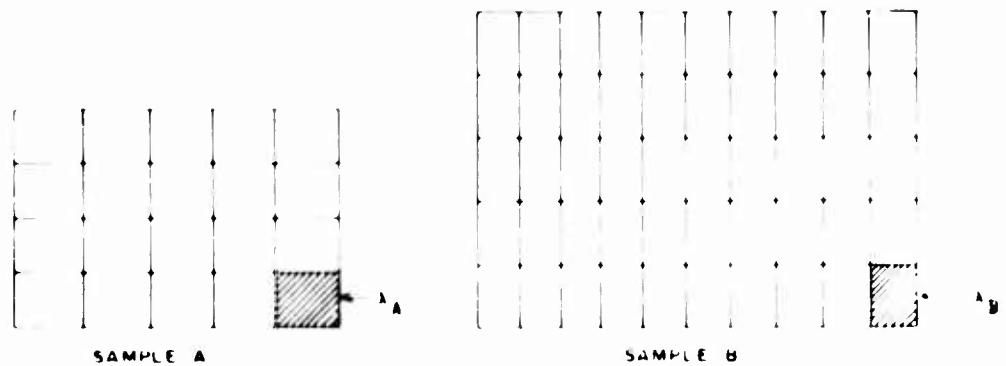


Figure 32. Example of the Significance of the Radioactive Decay Constant

#### NOTE

In sample A, one-twentieth of the sample decays in one unit time and, therefore,  $\lambda_A = 0.05$ . Sample B is less active, for  $\lambda_B = 1/50 = 0.02$ .

*Rule 1* If there are  $N$  atoms in a sample at some moment, and if  $\lambda$  expresses the fraction decaying in a unit time,  $N\lambda$  is the number per unit time actually decaying at that moment

c. For example,  $\lambda$  for U-238 is  $1.51 \times 10^{-10} \text{ yr}^{-1}$ , and since 1 gram atomic weight of U-238 contains  $6.02 \times 10^{23}$  atoms (Avogadro's Number), there will be  $(6.02 \times 10^{23})(1.51 \times 10^{-10})$  or  $9 \times 10^{13}$  decays per year in that much U-238.

d. The standard unit for measuring disintegration rate is the curie. One curie is defined as  $3.7 \times 10^{10}$  disintegrations per second. Since there are  $3.1 \times 10^7$  seconds in a year, the curie strength of one gaw of  ${}^{238}\text{U}$  is:

$$\frac{9 \times 10^{13} \text{ dis/year}}{(3.1 \times 10^7 \text{ sec/year})(3.7 \times 10^{10} \text{ dis/sec/curie})} = 10^{-4} \text{ curies}$$

e. To find the number of curies or the curie strength of a radioactive substance at any instant, we can use the following formula:

$$C = \frac{N\lambda}{3.7 \times 10^{10}}$$

$N$  is the number of radioactive atoms which are present at the time the curie strength is wanted.  $\lambda$  is the decay constant, but it must be expressed in seconds<sup>-1</sup> since the constant  $3.7 \times 10^{10}$  is in disintegrations per second in the definition of a curie.

f. The definition of the curie was originally based on the radioactivity of 1 gram of  $^{226}\text{Ra}$ , for which  $\lambda$  is  $1.38 \times 10^{-12} \text{ sec}^{-1}$ . One gram of this isotope is one two-hundred-and-twenty-sixth of a gaw and, therefore, contains:

$$1/226 (6.03 \times 10^{23}) = 2.66 \times 10^{21} \text{ atoms.}$$

Its activity then is:

$$\begin{aligned} N\lambda &= (2.66 \times 10^{21} \text{ atoms}) (1.38 \times 10^{-12} \text{ sec}^{-1}) \\ &= 3.71 \times 10^{10} \text{ disintegrations/sec} \\ &= 1 \text{ curie.} \end{aligned}$$

At present though, a curie is defined simply as  $3.7 \times 10^{10}$  disintegrations per second and is not defined in terms of a particular isotope.

g. A second useful fact about radioactive decay is the exponential decay law:

*Rule II. If a sample originally contains  $N_0$  radioactive atoms, the number of atoms left after a time,  $t$ , is given by the formula:<sup>1</sup>*

$$N = N_0 e^{-\lambda t}.$$

---

<sup>1</sup> This formula results from the original observation that the ratio of the number of atoms decaying in a unit time to the number present is a constant  $\lambda$ . Using the symbol  $\Delta$  to indicate the "change in...",  $\Delta N$  is read the change in  $N$ ,  $\Delta t$  becomes the change in time, and the above statement can be written mathematically:

$$\frac{\Delta N}{\Delta t} = -\lambda N$$

This could be put in differential form as,  $\frac{dN}{dt} = -\lambda N$  or  $\frac{dN}{N} = -\lambda dt$ .

Integrating from time  $t = 0$ , when there are  $N_0$  atoms, to time  $t = t$ , when there is the unknown number of atoms,  $N$ , left:

$$\int_{N_0}^N \frac{dN}{N} = -\lambda \int_0^t dt$$

$$\ln \frac{N}{N_0} = -\lambda t \quad \text{or} \quad N = N_0 e^{-\lambda t}.$$



h. One of the most useful characteristics of radioactivity is half life, which is the time for one-half of a sample of material to decay. This time is labeled  $t_{1/2}$  and can be calculated from the above decay law. When one-half  $N_0$  atoms have decayed,  $N = N_0/2$ . Therefore

$$\frac{N_0/2}{N_0} = \frac{1}{2} = e^{-\lambda t_{1/2}}$$

$$\ln 1/2 = -0.693 = -\lambda t_{1/2}$$

$$\text{Therefore, } t_{1/2} = \frac{0.693}{\lambda}.$$

i. Half life can be directly calculated from the decay constant and vice versa. Half life is more frequently quoted than the decay constant for a radioactive material. The usefulness of the radioactive decay law and half life are brought out by the following examples

(1) The half life of  ${}_{11}\text{Na}^{24}$  is 15 hours. If a sample of this isotope originally contains 48 grams, how many hours will be required to reduce this sample to 9 grams?

$$N_0 = 48 \text{ grams}$$

$$N = 9 \text{ grams}$$

$$\lambda \text{ for } {}_{11}\text{Na}^{24} = 0.693/15 = 4.6 \times 10^{-2} \text{ hr}^{-1}.$$

Substitution in the decay law gives:

$$9 = 48e^{-4.6 \times 10^{-2}t}$$

$$\text{or, } \frac{3}{16} = e^{-4.6 \times 10^{-2}t}.$$

Note that  $N$  and  $N_0$  do not have to be converted explicitly into numbers of atoms per sample, providing that they are both expressed in units proportional to this quantity, such as grams or curies. Since  $3/16$  can be written as  $e^{-1.68}$ , this becomes:

$$e^{-1.68} = e^{-4.6 \times 10^{-2}t}$$

$$\text{or } -1.68 = -4.6 \times 10^{-2}t$$

$$\text{and } t = 36.5 \text{ hours.}$$

The concept of half life serves as a useful check for this solution since in 1 half life the sample is reduced to 24 grams, in 2 half lives, it is reduced to 12 grams, and therefore, it would take about 2-1/2 half lives to reduce it to 9 grams. The 2-1/2 half lives are 37.5 hours, which compares favorably with the calculated and correct value of 36.5 hours.

(2) The initial curie strength of a sample of Po-210 is 0.50 curies. Calculate the curie strength after 20 days using the  ${}_{84}\text{Po}^{210}$  half life as 138.5 days.

For  ${}_{84}\text{Po}^{210}$ ,  $\lambda = 0.693/138.5 \text{ days} = 0.005 \text{ days}^{-1}$

$$C = 0.50 e^{-0.005 (20)}$$

$$0.50 (0.90) = 0.45 \text{ curies.}$$

j. The above calculations are often tedious and inconvenient and require the use of either a log log slide rule or a set of logarithms. Such calculations can be speeded up by use of a nomogram. See figure 33.

k. By placing a straightedge on the appropriate positions on the half life and time of decay scales, the fraction of radioactive material left or the fraction of radioactive material decayed can be read at the straightedge intersection with the scale on the right. They could also be used to give the relative curie strength remaining. Be sure to state half life and time of decay in the same units.

l. Example 1. For a radioisotope whose half life is 300 days (half-life scale) after 30 days (time scale) 0.068 (6.8 percent) will have decayed and 0.932 (93.2 percent) will remain (right-hand scale).

m. Example 2. If it is desired to let a radioisotope whose half life is 300 days decay to 64 percent of its original activity, it is necessary to wait 200 days (time scale).

#### 104. RADIOACTIVE DECAY SERIES<sup>1</sup>

a. Naturally occurring radioactive nuclides, in general, decay into new nuclides which are also radioactive. The process continues until some stable, nonradioactive nuclide is formed. The process then halts. The intermediate nuclides form a radioactive decay series.

<sup>1</sup> The detailed decay chains for the four decay series are presented to give the student understanding of the general principles involved. The student should be able to summarize these detailed decay chains.

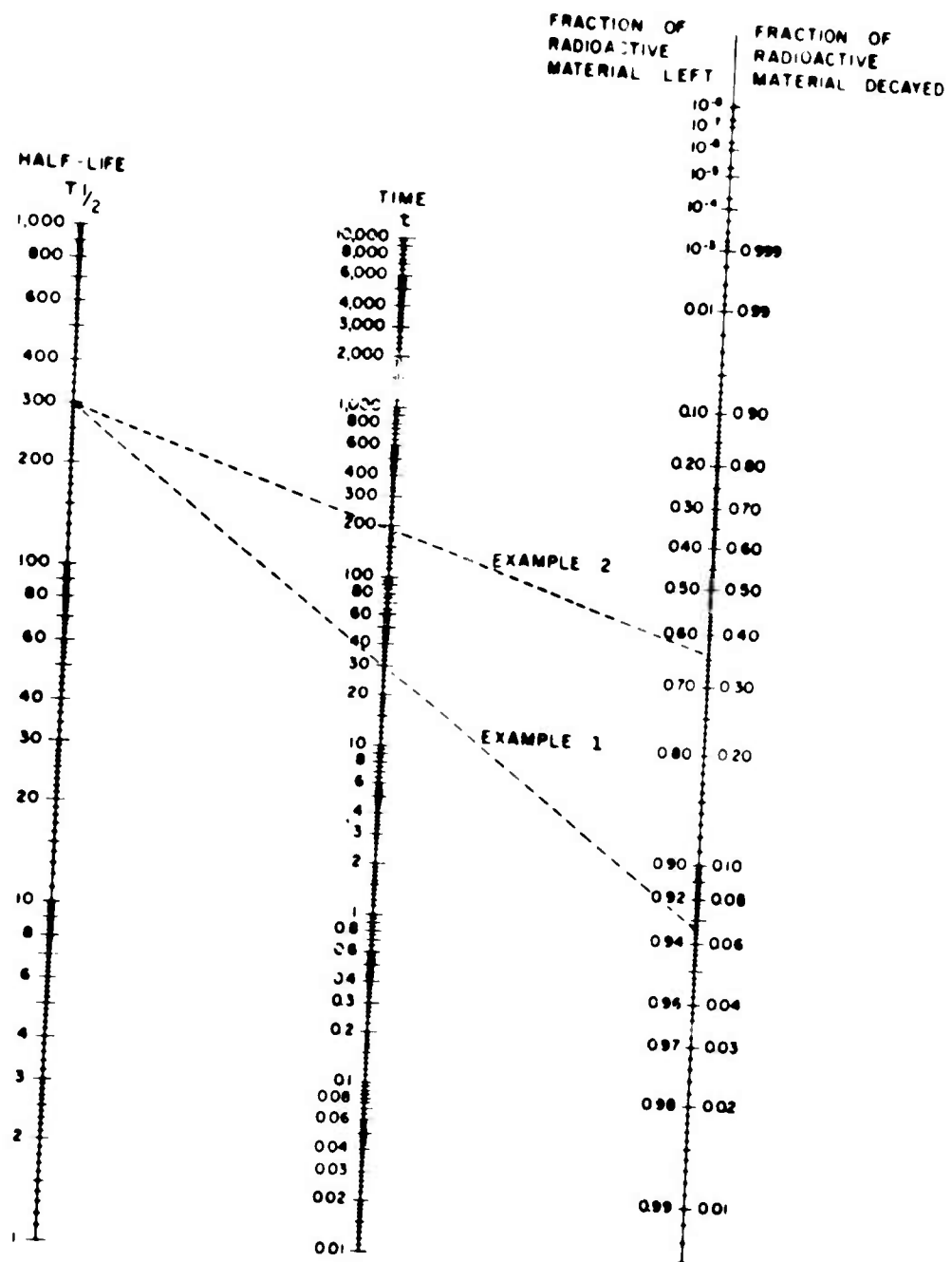


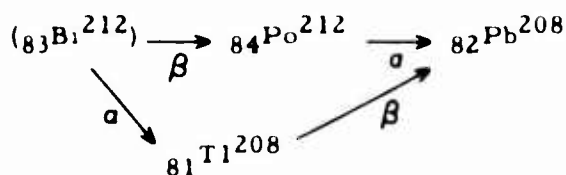
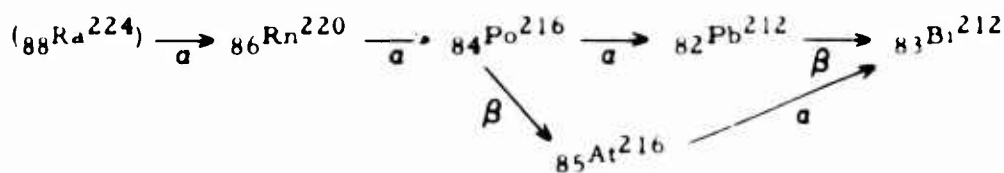
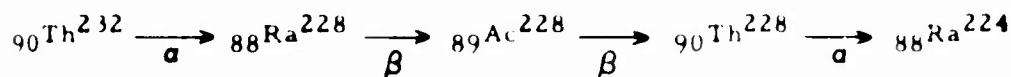
Figure 33. Nomogram for Radioactive Decay



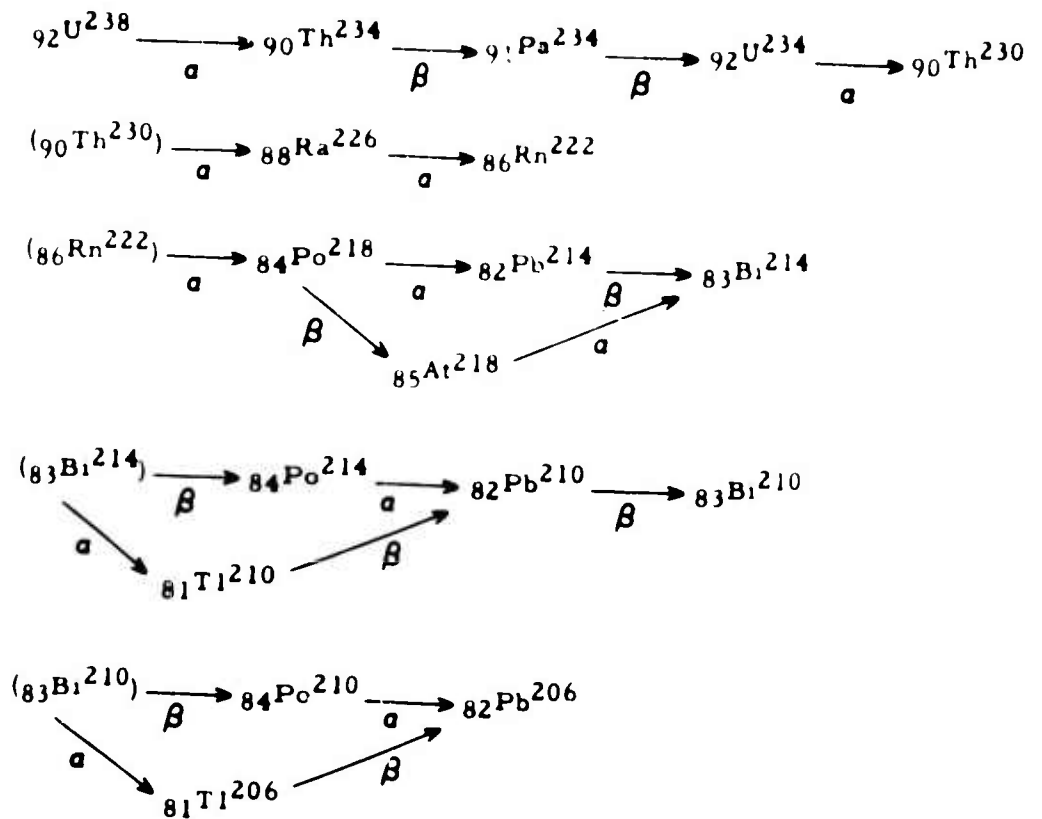
ELEMENT	SYMBOLS	HALF LIFE (T <sub>1/2</sub> )	TYPE OF EMISSION	RANGES IN AIR OR ENERGY PARTICLE EMITTED: $\alpha$ IN CMs, $\beta$ AND $\gamma$ IN MEV.
Uranium	${}_{92}\text{U}^{238}$ (UI)	$4.4 \times 10^9$ years	$\alpha$	2.67 cm.
Thorium	${}_{90}\text{Th}^{234}$ (UI <sub>1</sub> )	24.5 days	$\beta^-$	0.13 Mev.
Protactinium	${}_{91}\text{Pa}^{234}$ (UI <sub>2</sub> )	1.14 minutes	$\beta^-$	2.32 Mev.
			$\gamma$	0.60 Mev.
Uranium	${}_{92}\text{U}^{234}$ (UII)	$3.4 \times 10^5$ years	$\alpha$	3.23 cm.
Thorium (Ionium)	${}_{90}\text{Th}^{230}$ (Io)	$8.3 \times 10^4$ years	$\alpha$	3.2 cm.
Radium	${}_{88}\text{Ra}^{226}$	1590 years	$\alpha$	3.39 cm.
			$\gamma$	0.19 Mev.
Radon	${}_{86}\text{Rn}^{222}$	3.825 days	$\alpha$	4.08 cm.
Polonium	${}_{84}\text{Po}^{218}$ (RaA)	3.05 minutes	$\alpha$	4.69 cm.
Lead	${}_{82}\text{Pb}^{214}$ (RaB)	26.8 minutes	$\beta^-$	0.65 Mev.
			$\gamma$	
Bismuth	${}_{83}\text{Bi}^{214}$ (RaC)	19.7 minutes	$\alpha$	4.1 cm.
			$\beta^-$	3.15 Mev.
			$\gamma$	1.6 Mev.
Polonium	${}_{84}\text{Po}^{214}$ (RaC')	10-6 seconds	$\alpha$	6.95 cm.
Thallium	${}_{81}\text{Tl}^{210}$ (RaC'')	1.32 minutes	$\beta^-$	1.60 Mev.
Lead	${}_{82}\text{Pb}^{210}$ (RaD)	22 years	$\beta^-$	0.0255 Mev.
			$\gamma$	0.047 Mev.
Bismuth	${}_{83}\text{Bi}^{210}$ (RaE)	5.0 days	$\beta^-$	1.17 Mev.
Polonium	${}_{84}\text{Po}^{210}$ (RaF)	140 days	$\alpha$	3.87 cm.
Lead	${}_{82}\text{Pb}^{206}$ (RaG)	Stable		

Figure 35. The Uranium Series

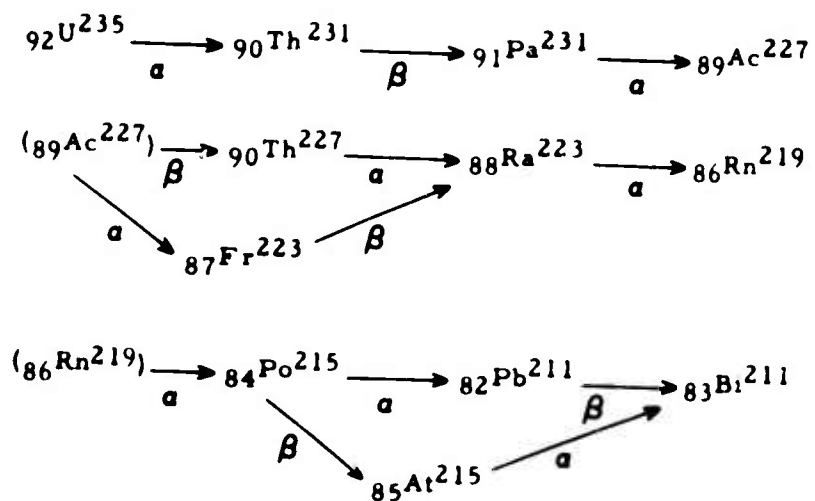
c. The thorium series starts with  ${}_{90}\text{Th}^{232}$  (the element in the series with the longest half life,  $t_{1/2} = 1.39 \times 10^{10}$  years) and works its way down to  ${}_{82}\text{Pb}^{208}$ .

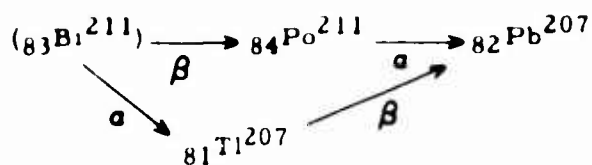


d. The uranium series starts with  ${}_{92}\text{U}^{238}$ , and decays to  ${}_{82}\text{Pb}^{206}$ . The half lives vary from  $4.51 \times 10^9$  years to  $1.5 \times 10^{-4}$  seconds. In each case in the uranium series, the atomic mass number may be represented by the number  $(4n + 2)$  where  $n$  is an integer ranging from 51 to 59. Therefore, the uranium series may be called the  $4n + 2$  series. Charts showing the uranium series decay scheme are given in figures 34 and 35. The complete sequence is:



c. The actinium series (formerly called actino-uranium) starts with  ${}^{92}\text{U}^{235}$  and ends with  ${}^{82}\text{Pb}^{207}$ .

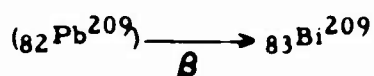
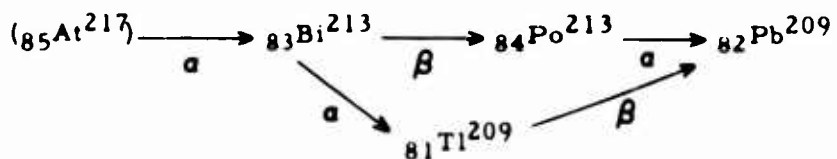
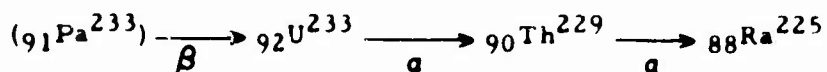
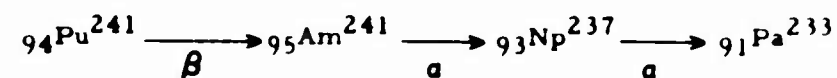




The half lives vary from  $7.1 \times 10^8$  years to  $10^{-4}$  seconds. This series has atomic mass numbers which may be represented as  $(4n + 3)$  where  $n$  is an integer from 51 to 58. Therefore, the actinium series may be called the  $4n + 3$  series.

f. In all of the preceding series, there have occurred instances in which a radio element decays in two ways,  $\alpha$  or  $\beta$ . The two 'daughter' products decay to the same next element in the series. These decay branches are shown with the most probable decay on the top, and the less likely branch on the bottom. The branching ratios are useful in the detailed study of radioactive nuclei.

g. The student should have noticed that the  $4n + 1$  series was missing. There may have been one early in the earth's history, but the longest half life in this series is  $2.2 \times 10^6$  years, belonging to neptunium,  $93\text{Np}^{237}$ . Thus, if this substance once existed naturally, it would be decayed now. Men have made neptunium and other trans-uranic elements, and this artificially induced series is now known. The neptunium series has the following sequence:





## 105. PROBLEMS

- a. If the  $n/p$  ratio is too high, what type of radioactivity is likely to be present?
- b. Three milligrams of Po-210 is what number of curies of Po? If the half life of Po-210 is 138 days, how much time will elapse before there is one curie left?
- c. What is the decay constant of radium, whose half life is 1590 years? How many grams are in a 6-mc radium source?
- d. Pu-240 decays by  $\alpha$ -emission to what isotope? This isotope is also  $\alpha$  active, as is its "daughter." Starting with Pu-240 and knowing the sequence of radiations is  $\alpha$ ,  $\alpha$ ,  $\alpha$ ,  $\beta^-$ ,  $\beta^-$ ,  $\alpha$ , and  $\alpha$ , what isotope is derived?

## SECTION II. INTERACTION OF RADIATION WITH MATTER

### 106. INTRODUCTION

Radiation is said to interact with a substance if it transfers some of its energy to that substance. Studies of these transfers of energy provide useful information about the nature of radiation. Therefore, knowledge of the mechanisms by which radiation interacts with matter is of great practical importance. Primarily, interactions afford a means of detection of radiations, but studies of the interaction of radiation with matter have also produced vital data about characteristic properties of matter itself.

### 107. IONIZATION

- a. The reader is reminded that the diameter of an atom is about 10,000 times the diameter of its nucleus and, therefore, the volume associated with an atom is, for the most part, empty space. When radiation travels through matter, it is likely to pass through many atoms with no detectable interaction. Also, since the cloud of electrons takes up most of an atom's volume, interactions are most likely to occur with electrons.
- b. Many electrons are bound to their atoms fairly loosely and, therefore, are easily freed by external sources of energy such as radiation. This process is called ionization, and the charged particles

which result are called ions. In general, ions are atomic particles characterized by a net electrical charge. Since an ionizing event produces two ions, ionization is usually measured in terms of the number of ion pairs produced. An electron and a positively charged particle are therefore an ion pair.

c. The number of ion pairs produced by radiation in a unit length of travel (usually one centimeter) is called the specific ionization. Specific ionization for a given radiation varies from one material (in which the ionization takes place) to another; but, in general, the energy necessary for ionization decreases with increasing atomic number,  $Z$ .

## 108. ALPHA PARTICLE INTERACTION

a. The most highly ionizing radiation is the alpha particle whose ionizing ability is attributable to its double, positive charge and relatively large mass and small velocity. An alpha particle ionizes when its electric field pulls electrons out of the atoms that it passes. In this process, energy is transferred from the alpha particle to the atom; and on the average, an alpha particle loses about 35.5 ev of energy in forming one ion pair. It is found, however, that this amount of energy is several times larger than the energy necessary to simply remove an electron. For example, it takes only 13.6 ev to ionize a hydrogen atom. The explanation is that the extra energy lost by the alpha is given to the electron as kinetic energy. Therefore, in addition to being freed, an electron is set into motion when an ion pair is formed. Example: A 5-Mev alpha particle is stopped in 3 centimeters of air. Calculate the specific ionizations of this particle.

$$\text{Total ion pairs} = \frac{5 \times 10^6 \text{ ev}}{35.5 \text{ ev/ion pair}} = 1.41 \times 10^5 \text{ ion pairs}$$

$$\text{Specific ionization} = \frac{1.41 \times 10^5 \text{ ion pair}}{3 \text{ cm}} = 4.7 \times 10^4 \text{ ion pair/cm}$$

b. It is also possible for an alpha particle to lose energy without ionization. Frequently, electrons will only receive enough energy to jump to an excited energy state, without being freed. This result is more probable when alpha particles are moving rapidly. The faster an alpha particle moves, the smaller will be the time spent in the vicinity of a particular atom. Therefore, a fast alpha particle has less time in which to transfer energy to an electron to produce an ionizing event. As a result, the specific ionization of alpha particles decreases with energy as shown in figure 36.

c. Another interesting observation about alpha particles is shown in figure 37 where the intensity of alpha particles is plotted

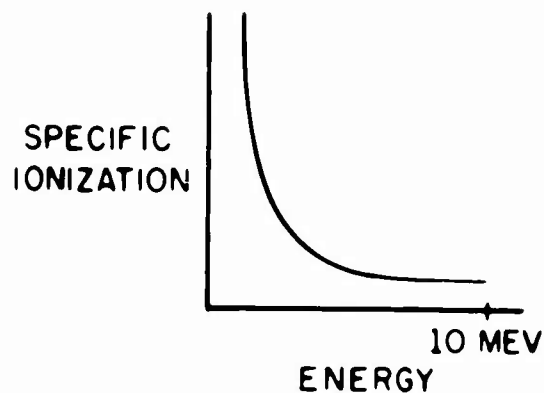


Figure 36. Specific Ionization Versus Energy for  $\alpha$  Particles

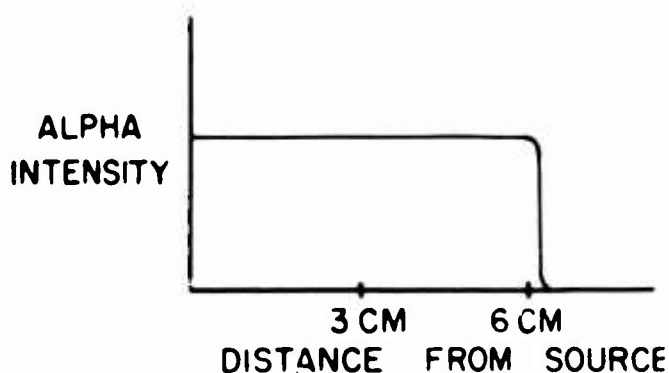


Figure 37. Alpha Intensity Versus Range

against distance from a source. This graph shows that all alpha particles from a given radioactive isotope have nearly the same range, which is attributed to the discrete energy levels in the radioactive nucleus. Because alpha particles from a given decay all have the same energy, they will all travel nearly the same distance in a given material. Slight differences in range among alpha particles of the same energy arise from the statistical nature of the ionizing events themselves.

d. For alpha particles of different energies, a variety of ranges result, but, in general, the maximum range of alpha particles is seldom over 8 centimeters in air. In a denser material, the range of alpha particles is considerably smaller, to the extent that they seldom are able to penetrate even tissue paper.

e. Figure 36 and figure 37 can be combined to produce a curve of specific ionization versus distance from a source. See figure 38. Note that as an alpha particle passes through a material, it is continually slowing down, which increases its ionizing ability. This accounts for the increase in specific ionization toward the end of the path of an alpha particle, as noted in figure 38.

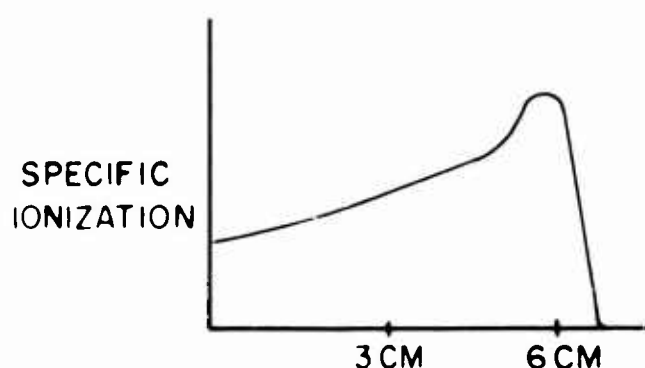
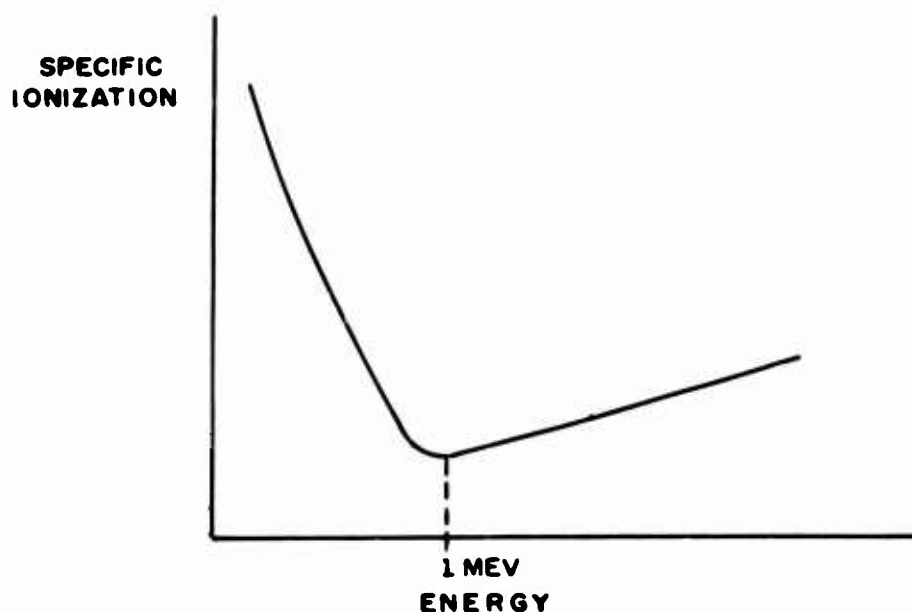


Figure 38. Specific Ionization Versus Range for  $\alpha$  Particles

#### 109. BETA PARTICLE INTERACTION

a. Beta particles, being charged electrically, are also capable of ionization in much the same manner that alpha particles ionize. However, the specific ionization is much smaller for beta particles (about one-hundredth that of alpha particles) because of their smaller mass and charge. With less mass, a beta particle travels much faster than an alpha with the same energy. To ionize an atom, a beta particle will have to come much closer to the atom than an alpha particle since its electric field is weaker and also less time is spent in the vicinity of any atom.

b. If specific ionization for beta particles is plotted against energy, a curve similar to that in figure 39 results. Note that for low



**Figure 39. Typical Plot of the Specific Ionization of  $\beta$  Particles Versus Energy**

energies, specific ionization falls off with increasing energy in a manner similar to that of alpha particles. It is found that, on the average, a beta particle loses about 32.5 ev in producing one ion pair in air.

c. The slight rise in specific ionization at high energies is not found with alpha particles. In the case of beta particles, it may be explained by a distortion of the electric and magnetic fields around a very rapidly moving charged particle (relativistic effects). The electric field about a slowly moving particle is symmetrical, as noted in figure 40. At very high velocities (near the velocity of light), the electric field becomes strengthened in the direction perpendicular to the direction of motion and causes the field of a rapidly moving particle to interact with atoms that would have been unaffected by a slower particle. See figure 41.

d. There is another means of interaction characteristic of high-speed beta particles. When a high-energy beta particle passes close to a heavy nucleus, it is deflected sharply by the strong electric field.

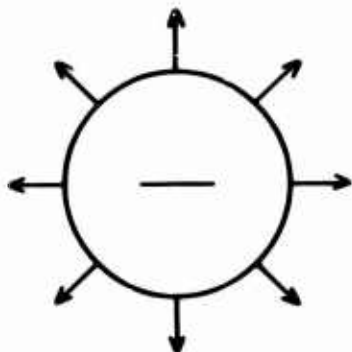


Figure 40. Electric  
Field Vectors for a  
Nonrelativistic Electron

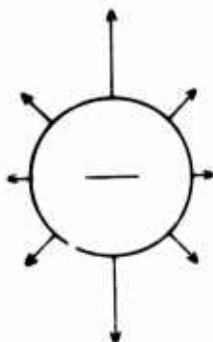


Figure 41. Electric  
Field Vectors for  
Relativistic Electron

In being deflected, a beta particle is found to emit energy in the form of an X-ray. Radiation produced in this way is called bremstrahlung, which is a German word meaning "braking radiation." This term arises because a beta is continually slowed down by successive bremstrahlung processes.

e. It should be noted that this process of deflecting charged particles to produce radiation does not apply to beta particles alone. Any moving charged particle will radiate when accelerated. However, beta particles are the only nuclear radiation light enough to be deflected (accelerated) to the extent that they will radiate X-rays. The energy of the radiated photons produced when slower particles are accelerated is usually insignificant.

f. Figure 42 shows how the two processes, ionization and bremstrahlung, contribute to the rate of energy loss by beta particles at different energies. Note that bremstrahlung is not significant below beta particle energies of about 1 Mev.

g. Beta particles of the same energy have a range which is nearly constant, just as was found in the case of alpha decays. However, if a plot is made of the number of beta particles with a given range versus range for the beta particles from a particular source, a curve resembling that in figure 43 results. As in the case of alpha emission, there is a definite upper limit to the range ( $R_{\max}$ ); but unlike alpha particles, the curve is not flat up to this range. See

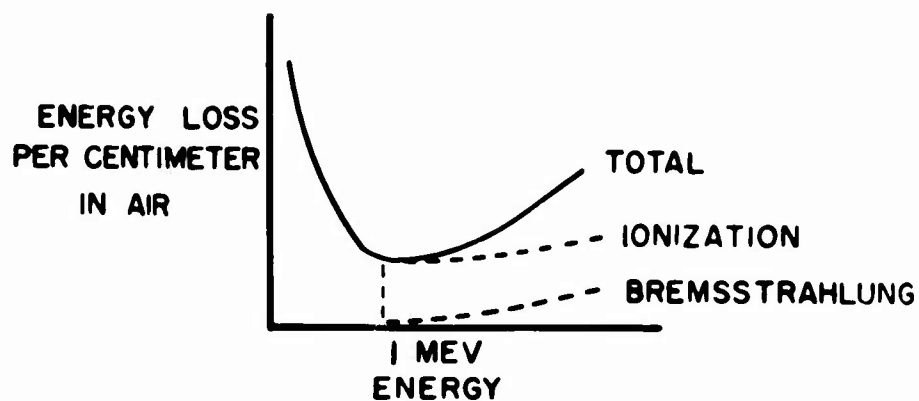


Figure 42. Energy Loss of  $\beta$  Particles

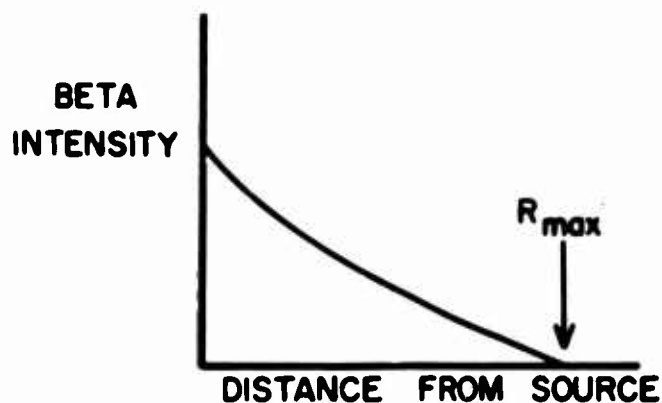


Figure 43. Beta Intensity Versus Range

figure 37. The continuous decrease in range of beta particles from a given beta emitter is accounted for by the fact that beta particles are not all emitted with the same energy, but rather with a distribution of energies similar to that shown in figure 30.

#### 110. GAMMA RAY INTERACTION

a. Because gamma rays have zero charge and are electromagnetic in nature, it might be expected that gamma interaction with matter would be impossible. This is incorrect, however, because gamma rays are able to interact in three interesting ways: through the photoelectric effect, the Compton effect, and by pair production.

(1) Photoelectric Effect.

(a) Under certain conditions, a gamma ray photon can eject an electron from a metal by means of a collision in which an atom (really an electron of the atom) completely absorbs the energy of the photon. Therefore, the electron absorbs an amount of energy equal to  $h\nu$  where  $\nu$  is the frequency of the photon and  $h$  is Planck's constant. The photoelectric effect produces electrons whose kinetic energy is given by:

$$\text{Kinetic energy} = h\nu - W$$

where  $W$  is the amount of energy that the electron loses within the material in escaping.

(b) Photoelectric ionization by gamma rays is primarily a low-energy interaction and falls off rapidly with energy. See figure 44. In general, the probability of this type of interaction is greatest for low-frequency gammas and high- $Z$  targets.

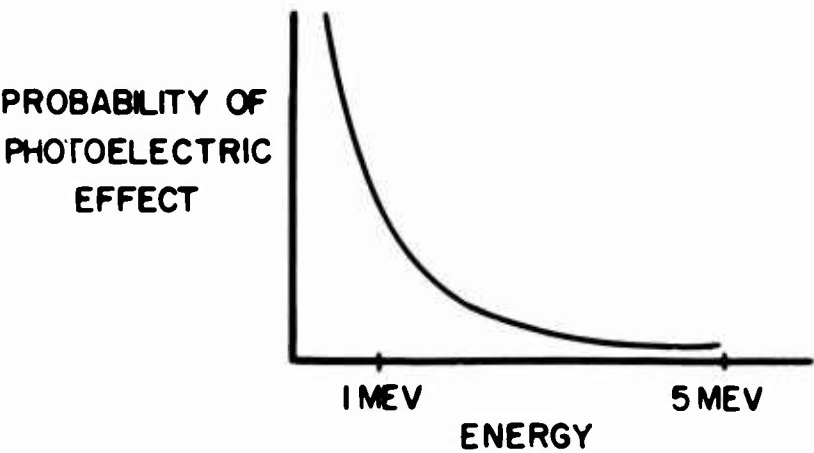


Figure 44. Typical Plot of the Dependence of the Photoelectric Effect Upon Energy



## (2) Compton Effect.

(a) Frequently, the interaction of a photon with an electron results in only part of the photon's energy being absorbed. This process, called the Compton effect (or Compton scattering), serves as a second means of ionization for photons. A graphic description of the Compton effect appears in figure 45. One special feature of the Compton effect is the change in frequency of the scattered photon. Because the incident photon has given up some of its energy to the freed electron, the energy of the scattered photon will be less. However, the energy of photons is proportional to frequency ( $E = h\nu$ ). Therefore, the scattered photon is found to have a new frequency which is lower than the original photon's frequency.

(b) The Compton effect extends to higher energies than the photoelectric effect but, like the latter, falls off with increasing energy. See figure 46. In general, the Compton effect is independent of atomic number of the absorbing medium.

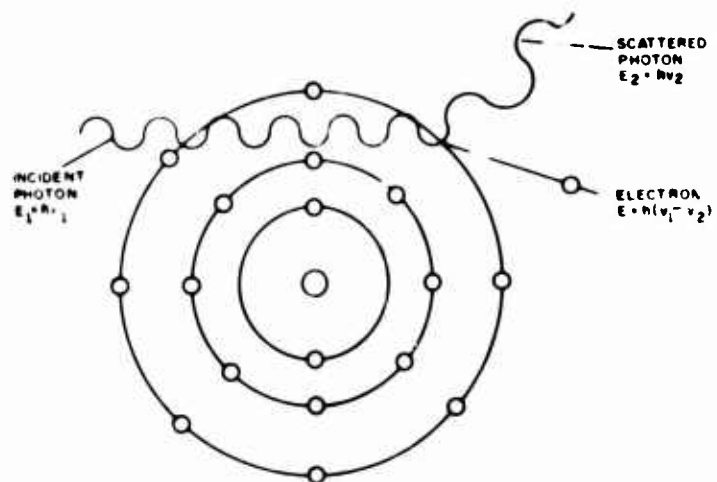


Figure 45. Compton Scattering

## (3) Pair Production.

(a) When a high energy photon passes near a nucleus, it may be transformed into an electron and a positron (a positive electron). This process is simply a transfer of energy from the

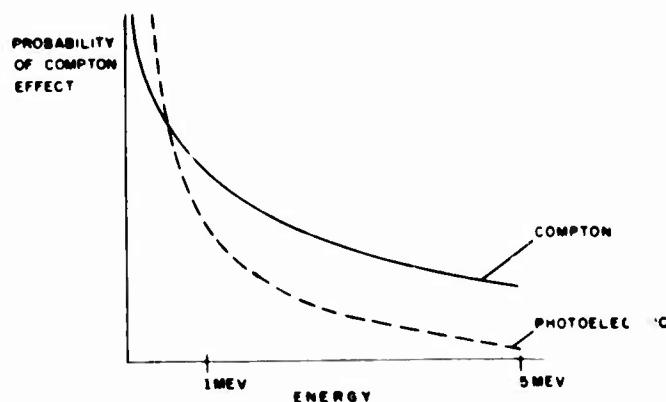


Figure 46. Variation of Compton Scattering With Energy of the Incident Gamma

electromagnetic form into mass, and therefore follows  $E = Mc^2$ . This brings up the question: "How much energy is necessary to create an electron and a positron?" Recall that 1 amu is equivalent to 931 Mev, and therefore:

$$2(0.00055)(931) = 1.02 \text{ Mev}$$

is the energy equivalent of 2 particles with mass of 0.00055 amu. It follows that 1.02 Mev is the minimum energy which a photon must possess in order to undergo pair production. Any excess energy over this threshold is given to the positron and electron as kinetic energy. It is not obvious why a third body, such as a nucleus, is necessary for pair production to take place. It is found, however, that energy cannot be converted into mass in the form of particles unless a third body is present to conserve momentum. Therefore, pair production does not take place in free space.

(b) A typical probability curve for pair production is shown in figure 47. Note that pair production increases with energy in contrast to the photoelectric and Compton processes.

(c) The creation of a positron and an electron by a photon is not the whole story of pair production, however, for positrons tend to combine with electrons, and in doing so become annihilated.

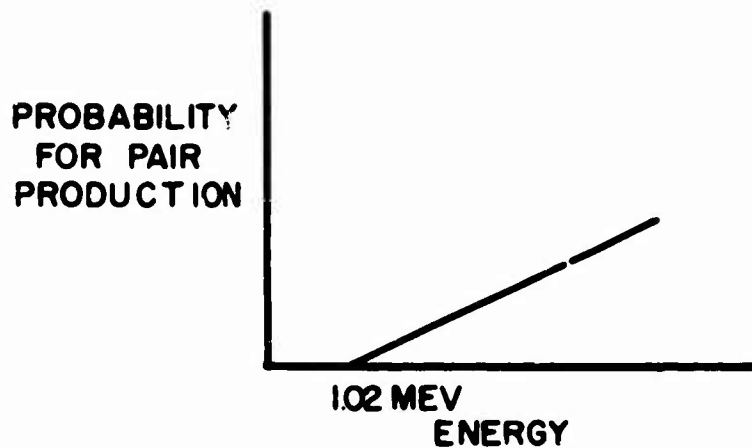


Figure 47. Dependence of Pair Production on Energy

The annihilation of positrons by electrons is an inverse pair production process, for here mass is converted into electromagnetic energy and two photons with energy 0.51 Mev are created and emitted in opposite directions. See figure 48.

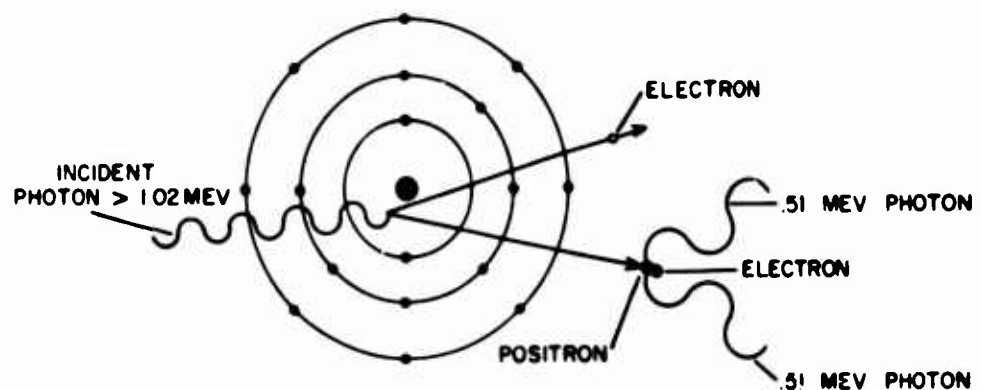


Figure 48. Pair Production and Subsequent Positron Annihilation

b. The three means of interaction for gamma rays are summarized in figure 49, which shows the relative probability for each

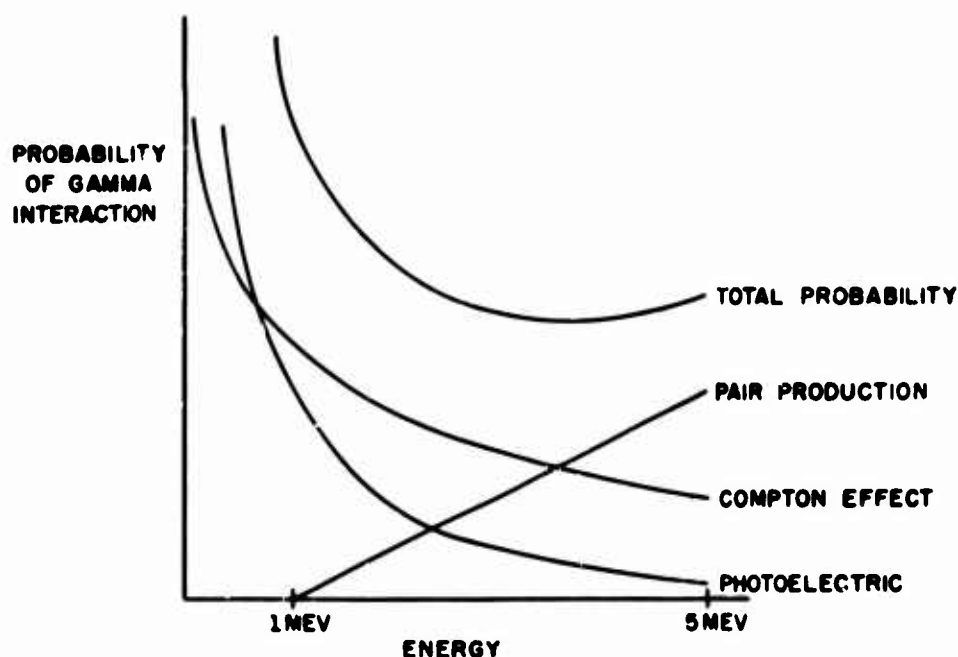


Figure 49. Interaction for Gamma Rays

reaction versus energy. The exact shape of this curve varies considerably from one material to another. In all cases, however, the curve is found to go through a definite minimum. This minimum is called the gamma ray window, because gamma rays of this energy pass through the material most easily. The position of the gamma window for lead is about 3 Mev, for iron about 7 Mev, and for aluminum about 20 Mev.

### 111. GAMMA ABSORPTION

a. Since the interaction of any radiation with matter results in a loss of energy by the radiation, this process is called absorption. Here, however, the discussion of absorption will be limited to gamma absorption only.

b. If a beam of gamma rays of intensity  $I_0$  strikes a very thin slab of material of thickness  $x$ , the gamma intensity is reduced to  $I$  according to the relationship:

$$I = I_0 e^{-\mu x}$$

where  $\mu$  is called the linear absorption coefficient and represents the fraction absorbed per unit length of travel. The letter  $x$  is the distance traveled expressed in the same units as  $\mu$ .

c. It is interesting to calculate from this formula the thickness of material necessary to cut the radiation intensity by one-half. This is called the half thickness of the material and is referred to frequently in discussions of absorption.

$$\text{Half thickness} = \frac{0.693}{\mu}.$$

Figure 50 is a plot of the half thicknesses of different materials versus the energy of the gamma rays.

d. The linear absorption coefficient for most materials varies with the state of the material (gas, liquid, or solid). For this reason, the density,  $\rho$ , of the material is often included, forming an absorption coefficient known as the mass absorption coefficient defined as:

$$\mu_m = \frac{\mu}{\rho}$$

This coefficient can be interpreted as the fraction of the gamma intensity which is absorbed in 1 gram of material through a surface area of 1 cm<sup>2</sup>. The mass absorption coefficient,  $\mu_m$ , has the advantage of being independent of the density of the absorbing material.

e. It is possible to use a nomogram to determine the relative fraction of gamma radiation that is transmitted through a given absorber. Such a nomogram is presented in figure 51 and is quite similar to the one used in chapter V for computing the fraction of material that has radioactively decayed.

f. In using the nomogram, one must be sure to use consistent units. Thus, both the half thickness and the thickness of absorbing material must have the same units.

g. Some typical examples are shown on figure 51. Thus, if we have 100 centimeters of a material whose half thickness is 20 centimeters for the gamma rays that are striking it, about 0.035 (3.5 percent) of the gamma rays will penetrate the material and 0.965 (96.5 percent) will be absorbed.

h. If the half thickness is 8 gms/cm<sup>2</sup>; 1 gm/cm<sup>2</sup> of material would transmit about 91.6 percent of the gamma rays. These would be the units used if mass absorption coefficients were given.

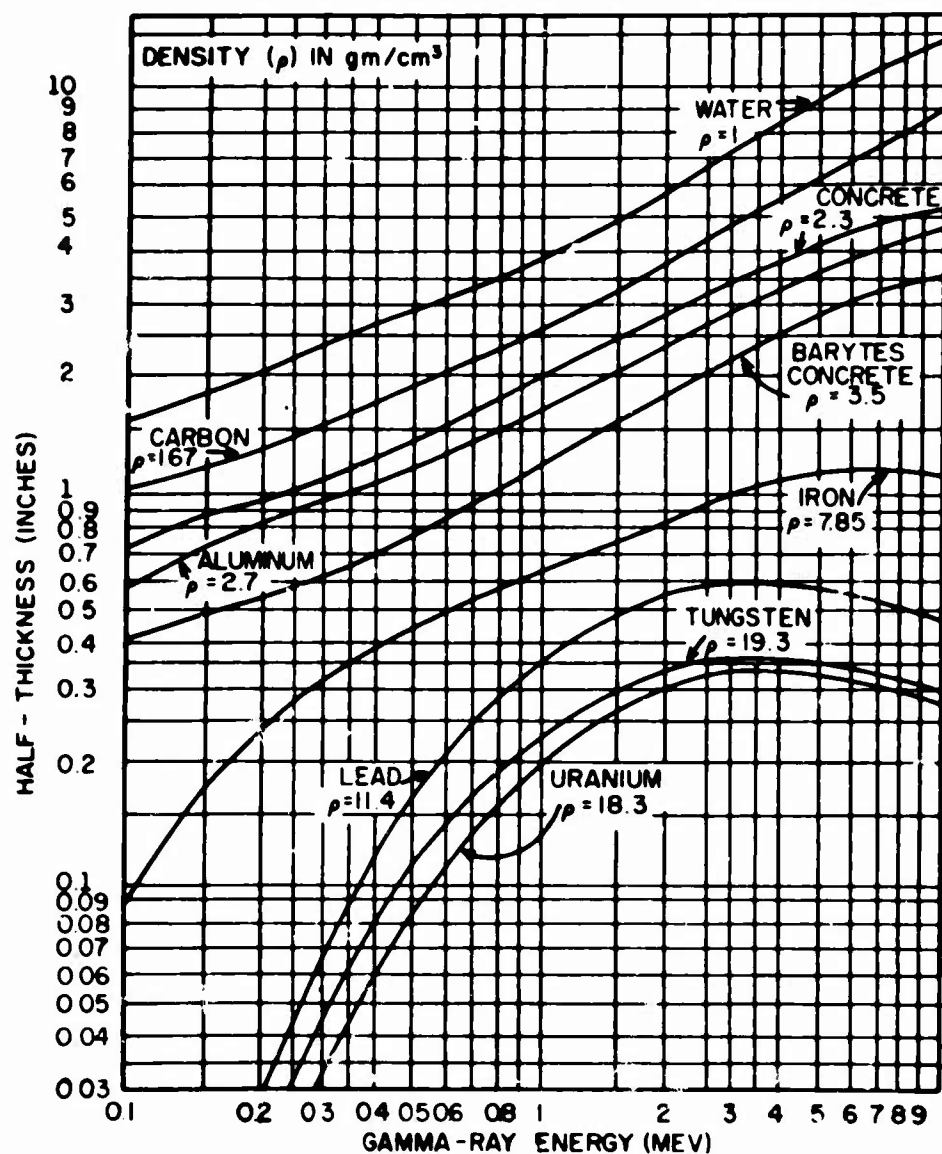


Figure 50. Half Thickness of Various Materials Versus Energy

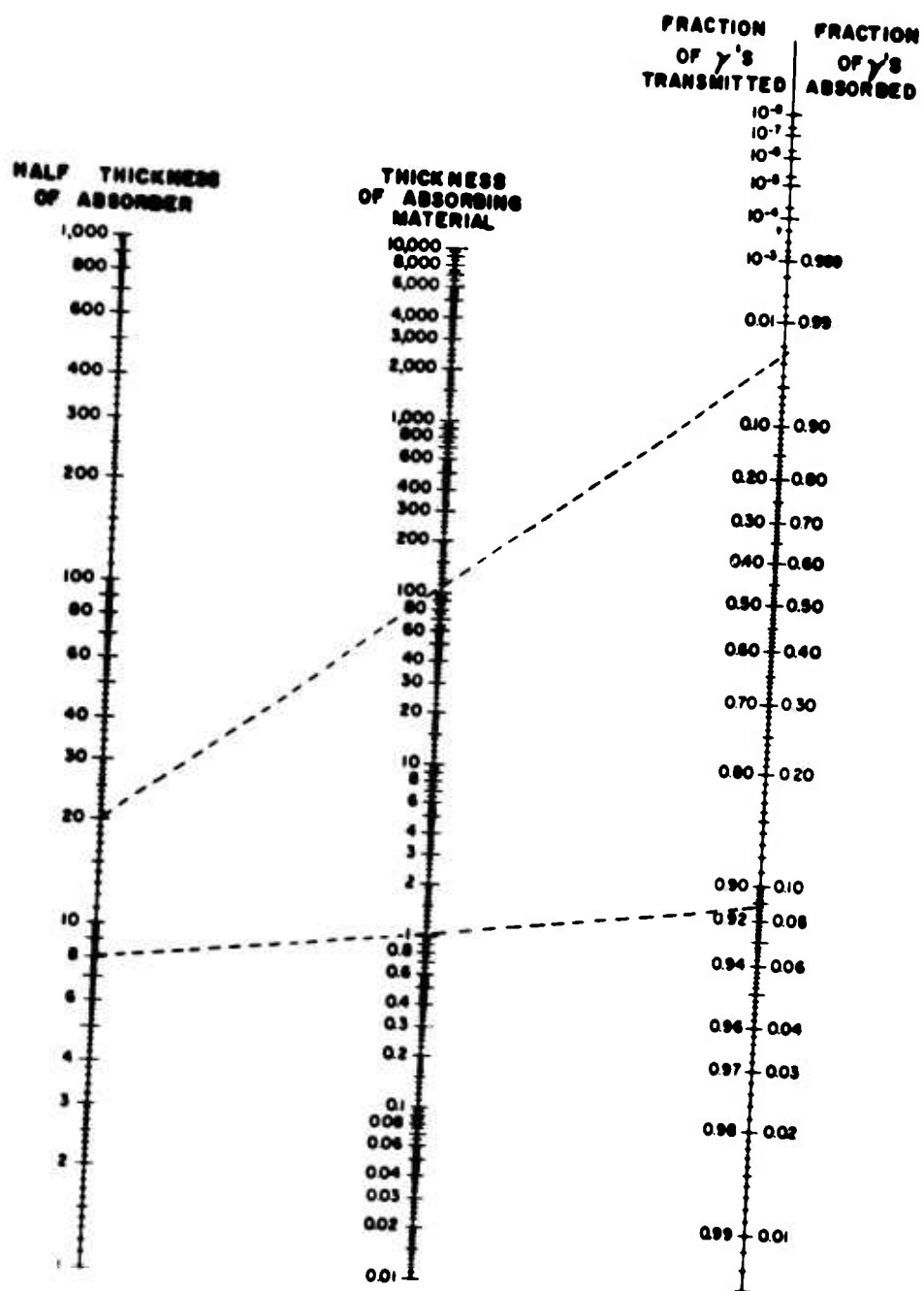


Figure 51. Nomogram for Gamma Ray Absorption

i. This nomogram also could be used to determine the half thickness of material if both the actual thickness of material and fraction of transmitted gammas were known. In all uses, the results will not strictly apply unless a very narrow beam of gamma rays is used.

j. This chapter has concentrated on the interactions of natural radiations with matter, and no mention has been made of other radiations such as neutrons, protons, etc. Neutron reactions are of sufficient importance to be left entirely for a later chapter. The reactions of other particles are partly included in the nuclear reactions chapter. Most of the techniques of atomic interaction of those particles involve the same principles outlined here for alpha, beta, and gamma radiations.



## CHAPTER 6

### NUCLEAR REACTIONS

#### SECTION I. GENERAL NUCLEAR REACTIONS

##### 112. INTRODUCTION

Nuclear reactions are, as implied, reactions between two or more nuclei. They are to be distinguished from chemical reactions by two major respects. In a chemical reaction, none of the species involved have any change in their nuclei. The second major respect is a consideration of the energies involved in nuclear reactions. At most, the energies involved in chemical reactions are in the 0 to 10-ev region. Nuclear reactions involve energies of the order of millions of electron volts.

##### a. Particles Entering Into Nuclear Reactions

(1) Almost all the particles listed in figure 24 may be involved in nuclear reactions. In addition to the particles listed, two or more nuclei may be involved.

(2) In a nuclear reaction, normally one type of nuclear particle is ejected or pulled out of some source with a relatively high velocity as the bombarding or incident particle. The bombarding particle is then directed against nuclei which are normally at rest. These are called target nuclei. The products are the recoil nucleus (usually considered to be the largest product nucleus) and the ejected (smaller) particle or particles.

(3) Bombarding particles are usually neutrons, protons, deuterons, or alpha particles. The charged particles, except for the alpha particles, are usually accelerated in an electrostatic field. The alpha particle sources may be radioactive sources such as  ${}_{84}\text{Po}^{210}$ .

##### b. Force Fields Around Nuclei

(1) Neutrons, when used as bombarding particles, seem to have very little difficulty in penetrating into a target nucleus. Although

there is a positively charged electric field due to the protons already in the target nucleus, the neutron effectively does not "see" this electric field since it has no charge of its own. When the neutron comes within approximately  $10^{-13}$  centimeters of the nucleus, it will be subject to the great cohesive (attractive) nuclear forces.

(2) For the proton, or any other positively charged particle, the above process does not hold. The proton, for example, will encounter a positively charged force field due to the protons in the nucleus. Since the proton is positively charged, the force field is repulsive in nature. The repulsive field increases very rapidly until the proton gets to about  $10^{-13}$  centimeters from the nucleus. The cohesive attractive forces start acting at this distance and overcome the repulsive forces. The proton may then enter the nucleus. The effect is as if there were a "wall" that the proton must penetrate. This "wall" is called a barrier. The barrier ends approximately  $10^{-12}$  centimeters from the center of the nucleus. See paragraph 96.

### 113. TYPES OF NUCLEAR REACTIONS

A nuclear reaction is said to occur whenever an incident particle enters a nuclear field; that is, when it enters the nucleus. Figures 52 to 56 are schematics of five basic nuclear reactions which can occur.

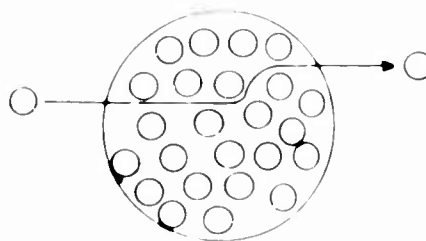
a. Elastic Scatter. One of the simplest nuclear reactions is the case of elastic scattering or elastic collision. This type of reaction is very similar to the collision of billiard balls. The conservation of momentum holds for the collision. No energy is transferred into exciting either the bombarding particle or the target nuclei. The criterion is that no energy be transferred into nuclear excitation, although there usually is a transfer to kinetic energy. As long as this holds, the collision is elastic. Recall that the bombarding particle and the ejected particles are the same, and that the recoil and target nuclei are the same.

b. Inelastic Scatter. This is a collision process in which energy is transferred from the collision into nuclear excitations. A good analogy is the collision between soft rubber balls. Physically, the bombarding particle may enter the target nucleus, or only touch it. However, energy is transferred to the target nucleus and excites it to an energy level which is above the ground state. When the excited target nucleus returns to the ground state, it gives up this excitation energy in the form of electromagnetic radiation. This electromagnetic



**Figure 52. Elastic Scatter**

radiation is gamma radiation. Thus, inelastic scatter is accompanied by gamma emission. Again, the bombarding and ejected particles are the same, and the target and recoil nuclei are the same.



**Figure 53. Inelastic Scatter**

c. **Capture Reactions.** Capture reactions usually involve bombardment by neutrons. However, this is not always the case, as some capture reactions are known to occur in which other particles are used for bombardment. In the case of a capture, the bombarding particle enters the target nucleus and remains. When it does so, however, it also excites the new recoil nucleus to an energy level above the ground state. When the recoil nucleus returns to the ground state, it releases the excitation energy in the form of gamma radiation. Hence, capture is accompanied by gamma emission. The recoil nucleus is different in nature from the target nucleus, and there is no ejected particle.

d. **Particle Ejection on Bombardment.** In this case the incident particle enters the target nucleus. The energy imparted to the newly

formed nucleus is enough to eject another particle from the nucleus. The recoil nucleus is usually left in an excited condition and returns to the ground state with the emission of gamma radiation.

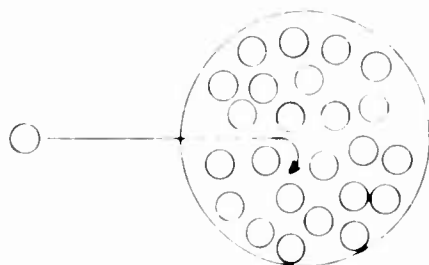


Figure 54. Capture

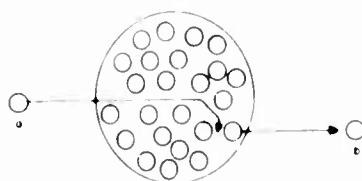
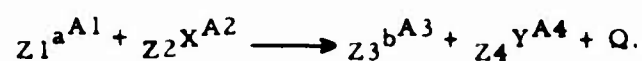


Figure 55. Particle Ejection on Bombardment

e. **Fission.** For fission reactions, a heavy nucleus is bombarded by some particle. Two large sized nuclei result, and several neutrons are emitted. The two recoil nuclei are called fission fragments. The fission fragments may be in an excited state. Actually, one can consider this class of reactions as a subclass of particle ejection on bombardment.

#### 114. NOMENCLATURE FOR NUCLEAR REACTIONS

a. The general equation for a nuclear reaction may be written in the following manner:



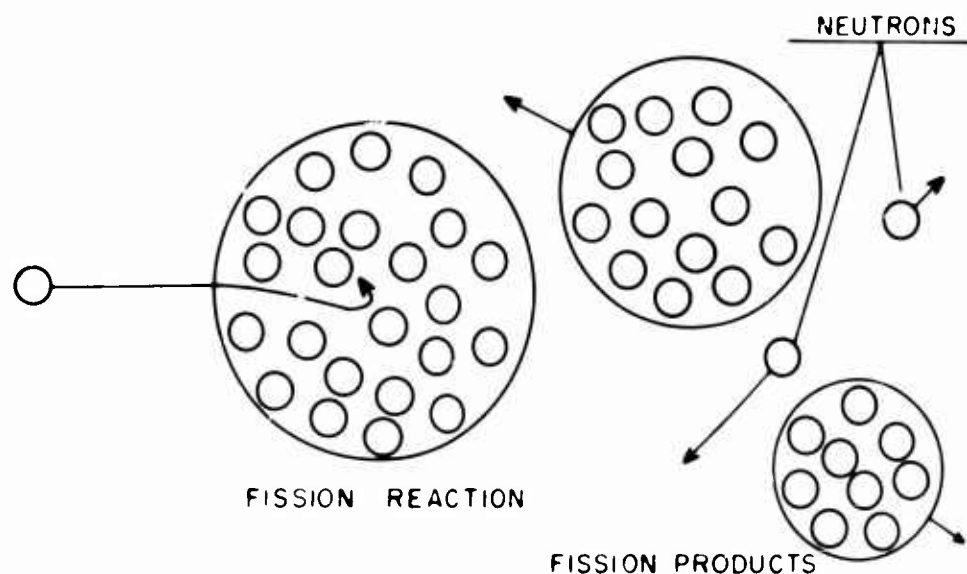
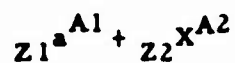


Figure 56. Fission

b. The symbol  ${}_Z^AW^A$  has the accepted connotation.  ${}_Z^aA^1$  is the bombarding or incident particle. For most reactions, it is a relatively light particle. Usual bombarding particles are:  ${}_0n^1$ ,  ${}_1H^1$ ,  ${}_1H^2$ ,  ${}_1H^3$ , and  ${}_2He^4$ , although others may be used.  ${}_Z^XA^2$  is the target nucleus. This at times may be called the parent nucleus.



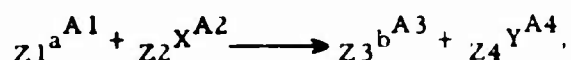
are called the reactants or the incoming mass.  ${}_Z^bA^3$  is the ejected particle. It is usually a light particle.  ${}_Z^YA^4$  is the recoil nucleus. It is also called the daughter nucleus. The sum  ${}_Z^bA^3 + {}_Z^YA^4$  are the products or the outgoing mass.

c. The term,  $Q$ , on the right in the general equation is the mass balance or energy term.

#### 115. RULES FOR NUCLEAR REACTIONS

a. There are a few rules which hold for nuclear reactions which shall be discussed before going into any specific reactions.

(1) Conservation of Nucleons. In a nuclear reaction, there is a conservation of the total number of nucleons. In the reaction,

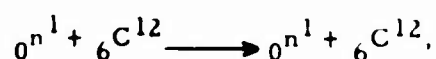


this means that  $A_1 + A_2 = A_3 + A_4$ . It does not mean that the total mass on each side of the equation is the same.

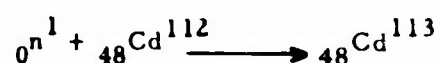
(2) Conservation of Nuclear Charge. Just as the number of nucleons is conserved, so also is the total nuclear charge. This holds also for nuclear reactions in which positrons and beta particles are involved. The reactions involve only the nucleus and not the orbital electrons. Thus, orbital electrons are not counted as nuclear charge. This conservation statement can be written as:  $Z_1 + Z_2 = Z_3 + Z_4$ . Any nuclear reaction which can be written having both  $A_1 + A_2 = A_3 + A_4$  and  $Z_1 + Z_2 = Z_3 + Z_4$  should be considered as a possibility.

(3) Conservation of Mass and Energy. The total mass is not conserved in a nuclear reaction. However, there is a conservation of the total of mass and energy. If the mass of the reactants is greater than the mass of the products, then energy must be released if the conservation of mass and energy is to hold. In the other case, where the mass of the products is greater than the mass of the reactants, then energy must be introduced to make the reaction go. The energy balance, or the mass difference, is taken into account by the Q term.

b. Example Reactions. The rules of nuclear reactions can be illustrated by considering a number of reactions of interest. The reaction,



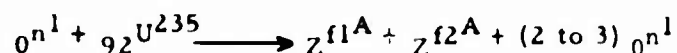
is an important case of elastic scatter which is used to slow neutrons. Graphite is used as a moderator.



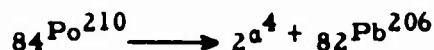
is a reaction used to capture neutrons.



is used as a neutron source.



is the well-known fission reaction. Radioactive decays may also be written as nuclear reactions.

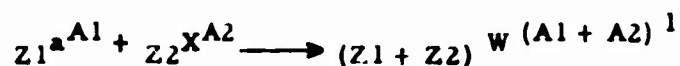


In all of these examples note that there is conservation of nucleons and conservation of nuclear charge. In addition, Q could be put on the right-hand side of each equation.

#### 116. MECHANISM FOR REACTION

a. Nuclear reactions can be understood much more clearly if we adopt the concept of a compound nucleus. The compound nucleus is an intermediate state which is postulated to provide an understandable path along which a nuclear reaction can proceed. When all the details of a reaction are known, the reaction mechanism is said to be known.

b. The compound nucleus is an unstable intermediate in a nuclear reaction. The evidence for the existence of the compound nucleus is fairly conclusive except for the case of elastic scattering. The formation of the compound nucleus may be written as:



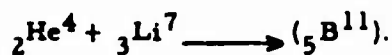
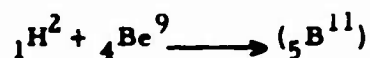
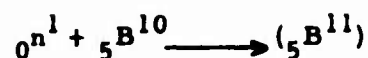
The compound nucleus is written as that nuclide which has an atomic number, that is the sum of the atomic numbers of the reactants. The total number of nucleons is also the sum of the nucleons of the reactants. The compound nucleus will usually be in an excited state. Note that compound nucleus can be formed any number of ways. For example, the formation of  $({}_5\text{B}^{11})^1$  can be had from:

#### NOTE

There is conservation of Z and A.

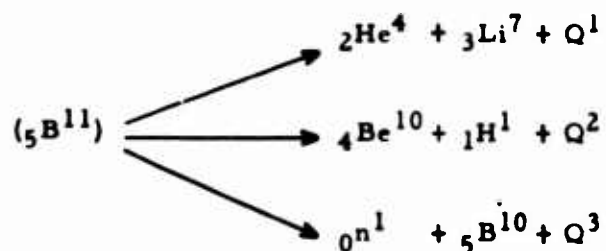
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<sup>1</sup> The parentheses indicates an excited nuclear state.

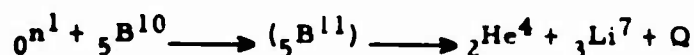


Therefore, the intermediate is independent of its formation to a great extent, the restrictions only being the conservation of Z and A. There is a good reason for this independence of formation of the compound nucleus. The half life of the compound nucleus is about  $10^{-12}$  to  $10^{-14}$  seconds. This time is much greater than the time required for a bombarding particle to traverse a target nucleus (assuming it is not slowed down very much in the process). Thus, the compound nucleus is not just that intermediate whose lifetime is the average length of time of a collision process. Let us calculate this collision or transit time. If one assumes a velocity of approximately  $10^9$  cm/sec for the bombarding particle and a typical target nucleus of diameter  $10^{-12}$  centimeters, the time required to traverse the target is about  $10^{-21}$  seconds. The compound nucleus lasts about  $10^8$  times longer than this. Essentially, then, the compound nucleus "forgot" how it was formed, although the energy level to which it is excited may vary with the reactants.

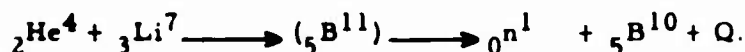
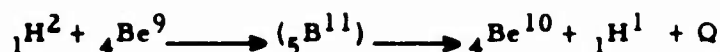
c. The breakup of the compound nucleus is dependent on the energy of the system. The possibilities for breakup can be easily listed. The only requirement is that of conservation of atomic number and the number of nucleons. For example,  $({}_5B^{11})$  can decay into:



Note that in each case there is a conservation of Z and A. We have not, as yet, considered which of these breakup possibilities is the most probable. There are a total of nine possible reactions using  $({}_5B^{11})$  as a compound nucleus. The possibilities are:







Reactions such as  ${}_0\text{n}^1 + {}_5\text{B}^{10} \longrightarrow {}_0\text{n}^1 + {}_5\text{B}^{10}$  can be elastic or inelastic collisions.

#### 117. SIGNIFICANCE OF Q

a. The probability of a reaction occurring is tied up with the energy balance or mass balance term, Q. Let us look again at the general equation,



The term Q is formally equivalent to a mass term. This is exactly the case. The energy balance term is the mass equivalent that is gained or lost in the reaction. The equation, as written, represents a nuclear reaction. Therefore, Q may be calculated from a mass balance of the equation. The mass equivalent of Q is:

$$Q = \text{Mass of reactants} - \text{Mass of products}.$$

If the reaction masses are in atomic mass units, the conversion to energy in Mev is:

$$Q (\text{Energy}) = (\text{Mass of reactants} - \text{Mass of products}) 931 \text{ Mev/amu}.$$

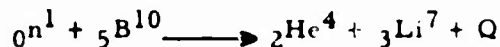
b. If the mass of reactants is greater than the mass of the products, mass is lost during the course of the reaction. Energy is therefore released. The reaction is called exoergic if energy is released (Q greater than zero).

c. If the mass of the reactants is less than the mass of the products, mass must be supplied in order for the reactions to go as written (Q less than zero). The only way for mass to be supplied is by the destruction of energy. Then, at least -Q (here Q is negative, so -Q is positive) amount of energy must be supplied to the reactants to make the reaction go as written. This amount of energy, -Q is called the threshold energy. When  $Q < 0$  and energy must be supplied to make the reaction go as written, the reaction is said to be endoergic.

#### 118. CALCULATION OF Q

a. The calculation of Q is a relatively easy matter if one has a

table of the masses of nuclei. A table of nucleon masses is generally not available; however, the usual tables of isotopic masses including the mass of the electrons (appendix V) can be readily used. Note that we always have conservation of  $Z$  for any nuclear reaction. Thus, if we used elemental masses, we will not be making any error since the same number of electrons appear on both sides of the equation, and there will not be any electrons created or destroyed.



Mass of the reactants:  ${}_0\text{n}^1 = 1.00894 \text{ amu}$

$${}_5\text{B}^{10} = \underline{10.01618 \text{ amu}}$$

Reactants = 11.02512 amu

Mass of products:  ${}_2\text{He}^4 = 4.00390 \text{ amu}$

$${}_3\text{Li}^7 = \underline{7.01822 \text{ amu}}$$

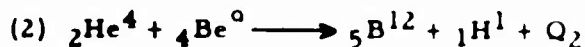
Products = 11.02212 amu

$$Q = 931 \frac{\text{Mev}}{\text{amu}} (11.02512 \text{ amu} - 11.02212 \text{ amu})$$

$$= 931 \frac{\text{Mev}}{\text{amu}} \times 0.00300 \text{ amu} = 2.79 \text{ Mev}$$

Note that  $Q$  is positive. This means that energy will be released during the reaction by a destruction of 0.00300 amu of mass. The reaction is exoergic.

b. Problem: Calculate  $Q$  for the following reactions:



Answers:  $Q_1 = 5.74 \text{ Mev}$ ,  $Q_2 = -7.64 \text{ Mev}$ , and  $Q_3 = -13.28 \text{ Mev}$ .

c. In reaction (2), the alpha particles would have to be

accelerated to at least 7.64 Mev in order to get the reaction to go as written. In reaction (3), at least 13.28 Mev of energy would have to be supplied to the reactants to get the reaction to go as written. Thus, 7.64 Mev and 13.28 Mev are the threshold energies. Both reactions are endoergic.

#### 119. PROBABILITY OF THE OCCURRENCE OF REACTIONS

a. The relative probability of a reaction to occur in a set of reactions with the same reactants can be estimated from the  $Q$ 's of the reactions. The reaction with the highest positive  $Q$  value will usually be the most probable. Reactions with negative  $Q$ 's will be least probable.

b. Consider the reactions illustrated above. Reaction (1) is the most probable since we do not have to supply energy to get the reaction to go. Reaction (2) is the next most probable; and (3) is the least probable. If 7.64 Mev of energy is supplied, only (1) and (2) can occur. But (1) will still be the most probable. If 13.28 Mev of energy is supplied, all the reactions can occur; (1) will predominate, (2) will be the next most prominent, and (3) will be the least probable reaction. Thus, the probability order, based on a  $Q$  scale, will hold for all energies. This probability relationship is called the  $Q$  rule.

c. We note here that the  $Q$  rule is a rule of thumb and many examples are known which violate this rule. Strictly speaking, we should know what sort of potential barrier there is for each possible reaction before a probability estimation is attempted. In addition to the potential barrier, thermodynamic considerations (entropy and free energy) should be consulted. The problem, on the whole, is extremely complex.

#### 120. CROSS SECTION

a. Probabilities for the occurrence of nuclear reactions are of great importance in nuclear physics. For this reason, quantitative measures of reaction probability are required. A measure of the probability of reaction occurrence (not strictly a true probability) is the cross section.

b. One can perhaps better grasp the concept of cross section by use of physical analogies rather than strict mathematical derivations. Let us consider the following case. Suppose a machinegun is locked into a given position and is firing at a target. The target will consist of two parts, an outer ring and a bull's-eye. The machinegun is assumed to have a fixed rate of fire. The assumption is also made that all bullets will hit the target in a random manner. For any given rate

of fire, there will be a certain number of bull's-eyes for a given time interval. The probability of hitting the bull's-eye will be the ratio of the number of bull's-eyes obtained to the total number of shots fired. But this will also be the ratio of the area of the bull's-eye to the total area of the target since the pattern of shots is assumed to be random. If the total area of the target is taken as unity, then a measure of probability of hitting the bull's-eye is just the area of the bull's-eye.

c. In a similar way, consider the area of the nucleus as seen by the bombarding particles, then a measure of the probability for reaction is a cross-sectional area. Let us expand this notion with another analogy to give some other characteristics of reaction.

d. Again set up a machinegun firing at a target. This time assume the target to be a cotton bale with steel balls imbedded within. Also, assume that the projectiles are of a strange material which will at times stick to the steel balls and not at other times and that the projectiles will completely go through cotton if there are no collisions with steel balls. We can now see a property of nuclear reactions. The number of "sticks" are going to depend on the density (number of balls per unit volume) of steel balls and the properties of the projectiles and the targets. This is a property of nuclear reactions.

e. If a unit area is picked, then the probability for reaction can be measured as the effective area for shots (or incident particles) that cause the reaction, in the same way as the area of the bull's-eye is a measure of the probability of hitting the bull's-eye. However, the effective area or cross section may be larger than the unit area.

f. The unit area is rather arbitrarily chosen as  $10^{-24} \text{ cm}^2$ . This is of the same order of magnitude as the area cut by a plane passing through the diameter of a typical nucleus. This unit is defined as the barn;  $1 \text{ barn} = 10^{-24} \text{ cm}^2$ . All nuclear cross sections will be measured in barns.

g. One should note that the cross section will depend upon the material being bombarded, the bombarding particle, the energy of the bombarding particle, and the particular reaction being considered; thus, the cross section for scatter will be different than that for capture, etc.

h. The symbol for cross section is  $\sigma$ . The total cross section is:

$$\sigma_t = \sigma_s + \sigma_c + \sigma_f + \dots$$

Total                  Scatter                  Capture                  Fission

## 121. MEAN FREE PATH

a. The mean free path for reaction is the mean distance a bombarding particle will travel once it has entered the target material. Obviously some bombarding particles will react immediately upon entering the target material while a few will be able to travel an appreciable distance before reacting.

b. This distance traveled will depend upon the density (number of atoms per unit volume) of the target material, since there will be more collisions the greater the density is, and hence a shorter mean free path. The distance traveled will also depend on the probability for reaction (cross section). Hence, the larger  $\sigma$  is, the shorter the distance is. The relationship is:

$$\lambda = \frac{1}{N\sigma}$$

where  $\lambda$  is mean free path,  $N$  is density in atoms/cm<sup>3</sup>, and  $\sigma$  is in cm<sup>2</sup> to give  $\lambda$  in cm. Note that, although  $\lambda$  is a function of the density,  $\sigma$  is independent of density.

c. The mean free path will also depend upon the reaction being considered. The total mean free path is given by:

$$1/\lambda_t = 1/\lambda_s + 1/\lambda_c + 1/\lambda_f + \dots$$

and

$$\sigma_t = \sigma_c + \sigma_s + \sigma_f.$$

d. Example: The thermal neutron capture cross section for cadmium is 7100 barns. What is the mean free path of a thermal neutron in Cd? The density of Cd is 8.64 gm/cm<sup>3</sup>.

$$\sigma_c = 7100 \text{ barns} = 7.1 \times 10^{-21} \text{ cm}^2$$

$$N = 8.64 \text{ g/cm}^3 \times \frac{1}{112 \text{ g/gaw}} \times 6.02 \times 10^{23} \frac{\text{atoms}}{\text{gaw}}$$

$$\lambda_c = \frac{112}{7.1 \times 10^{-21} \times 8.64 \times 6.02 \times 10^{23}} \text{ cm}$$

$$\lambda_c = 3.03 \times 10^{-3} \text{ cm}$$

## 122. RESONANCE REACTIONS

Because nuclei have discrete energy levels, there are conditions for which reaction probability can be extremely large. That is, it is possible to supply just the proper amount of energy to the reactants so that a very high cross section for reaction can occur. Essentially, the proper amount of energy is introduced so that the compound nucleus can be excited to a higher energy level. Reaction probability then increases. The energy for which this occurs is called the resonance energy. The peak in the cross section versus energy curve is called the resonance peak.

## 123. PROBLEMS

- What is the compound nucleus for  ${}_7\text{N}^{14}(\alpha, p)$  reaction? What is the product of this reaction?
- Calculate  $Q$  for:  ${}_4\text{Be}^9(\alpha, n){}_6\text{C}^{12}$ .
- Calculate  $Q$  for the reaction:  ${}_1\text{H}^3 \longrightarrow {}_2\text{He}^3 + \beta^-$ .
- The total cross section for a nuclear reaction is 0.6 barns. The scatter cross section is 0.45 barns, and the capture cross section is 0.05 barns. What is the fission cross section?
- A certain material has a density of  $5.65 \text{ gm/cm}^3$ . It has a gaw of 350 gm/mole. The thermal neutron capture cross section is 0.5 barn. What is the mean free path of neutrons in this material?

## SECTION II. NEUTRON REACTIONS

### 124. HISTORICAL

- The discovery of the neutron took place in several distinct stages. The earliest recorded observations involving the neutron dates to the early 1930's in an experiment in which alpha particles were used to bombard beryllium metal. A resulting extremely penetrating radiation was obtained. The fact that radiation was given off was evidenced by secondary effects. The source of the alpha particles was  ${}_{84}\text{Po}^{210}$ .
- The second stage was an attempt to identify the penetrating radiation which resulted from the beryllium bombardment. Paraffin

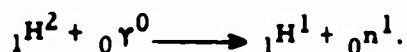
blocks placed in the path of the penetrating radiation emitted protons which were readily identified. However, the penetrating radiation itself was not identified.

c. The identification of the neutron itself came next. The simple experiments which identify the charge on a particle failed to detect any charge. The charge on the particle is therefore zero. The problem was to determine the mass of this charge-less particle. The mass was determined by an analysis of the recoil energy of particles involved in neutron reactions.

d. Of course, the difficulty in the identification of the neutron was the fact that it had zero charge. The mass, as determined from recoil experiments, was not accurately known but was determined to be about the same as a proton.

## 125. MASS OF THE NEUTRON

The accurate determination of the mass of the neutron was obtained from the energy balance of a nuclear reaction. The nuclear reaction used is the photo disintegration of the deuteron by gamma radiation:



The minimum energy of the  $\gamma$  ray needed to break up the deuterium atom is 2.21 Mev. This corresponds to 0.00238 amu in mass.

$$\begin{aligned} M({}_0\text{n}^1) &= M({}_1\text{H}^2) + 0.00238 - M({}_1\text{H}^1) \\ &= 2.01472 + 0.00238 - 1.00813 \\ &= 1.00897 \text{ amu.} \end{aligned}$$

More recent determinations have yielded 1.00894 amu for the mass of the neutron.

## 126. ENERGY CLASSIFICATION OF NEUTRONS

The classification of neutrons is a fairly arbitrary affair. However, since the cross section for reaction depends very much on the kinetic energy of the neutron, a classification based on this energy is a useful device. See table 6.

Table 6. Energy Classification of Neutrons

<u>Name</u>	<u>Energy Range</u>
Thermal neutrons	1/40 to 1/30 ev
Slow neutrons	1/30 to 100 ev
Intermediate neutrons	100 to 0.1 Mev
Fast neutrons	> 0.1 Mev

## 127. NEUTRON SOURCES

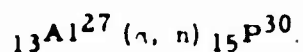
Since neutron reactions are of utmost importance in nuclear physics, available sources of neutrons are needed. Listed below are a number of general reactions which will yield neutrons of various energy classes.

a. ( $\gamma$ , n) Reactions. The photo disintegration of deuterons which was used for mass determination of the neutron is a classic example.

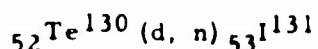
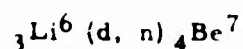


Neutrons of various energy classes can be obtained depending on  $\sigma$  and the energy of the  $\gamma$  ray. For ( $\gamma$ , n) reactions,  $Q$  is invariably negative, and energy must be supplied with the  $\gamma$  ray. A good source is also the reaction  ${}_4\text{Be}^9 (\gamma, n) {}_4\text{Be}^8$  with a minimum  $\gamma$  energy of 1.62 Mev. The  ${}_4\text{Be}^8$ , in turn, is radioactive.

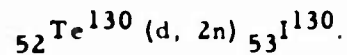
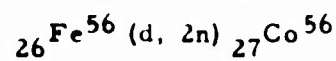
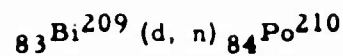
b. ( $\alpha$ , n) Reactions. The classic example is the alpha particle bombardment of Be-9 ( ${}_4\text{Be}^9 (\alpha, n) {}_6\text{C}^{12}$ ). The neutrons ejected in this reaction are of about 5.5 Mev energy. Another example of the ( $\alpha$ , n) reaction is:



c. (d, n) Reactions. The reaction  ${}_4\text{Be}^9 (d, n) {}_5\text{B}^{10}$  is a useful source of neutrons. The deuterons are accelerated in a cyclotron.  ${}_3\text{Li}^7 (d, n) {}_4\text{Be}^8$  gives neutrons up to 15 Mev.  ${}_1\text{H}^2 (d, n) {}_2\text{He}^3$  gives neutrons up to 3.2 Mev. Other examples of the (d, n) reaction, which might be used as sources, are:







d. (p, n) Reaction.



Reactions of the (p, 2n) variety have also been observed using very high-energy protons.

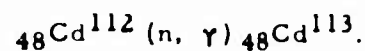
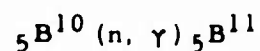
e. Fission Reaction. This reaction provides the largest available neutron fluxes. It is often carried out in a nuclear reactor or pile. The fission reaction chosen is usually the slow neutron fission of U-235 or Pu-239. Two to three neutrons are ejected for each fission that occurs. The neutrons ejected from U-235 fission have a mean energy of about 0.8 Mev.

## 128. NEUTRON INDUCED REACTIONS

a. Since the neutron has no charge associated with itself, the problem of penetrating a target nucleus is a relatively easy matter. It should be stressed that in addition to particles ejected, or gamma emission which is evolved during the neutron reaction, there is, in a great many cases, a radioactivity associated with the daughter nucleus. This is called neutron induced radioactivity. As a important example, fission fragments are, in general, radioactive.

b. Thermal Neutron Reactions. A large variety of neutron reactions can occur depending mainly on the cross section for a particular reaction. The reactions considered in this section have fairly large cross sections for thermal neutrons.

(1) (n,  $\gamma$ ) Reactions. These are in the radiative capture class (sometimes called simply absorption). There are a huge number of specific reactions in this category. The following are two examples of great importance in nuclear physics:



Both of these materials have unusually large neutron capture cross sections. Thus, these materials can be used to control the population

of neutrons in a given volume of material. There are a few other materials with larger capture cross sections than cadmium or boron, but these are not found in abundance. Figure 57 shows the variation of  $\sigma$  with energy for cadmium and boron.

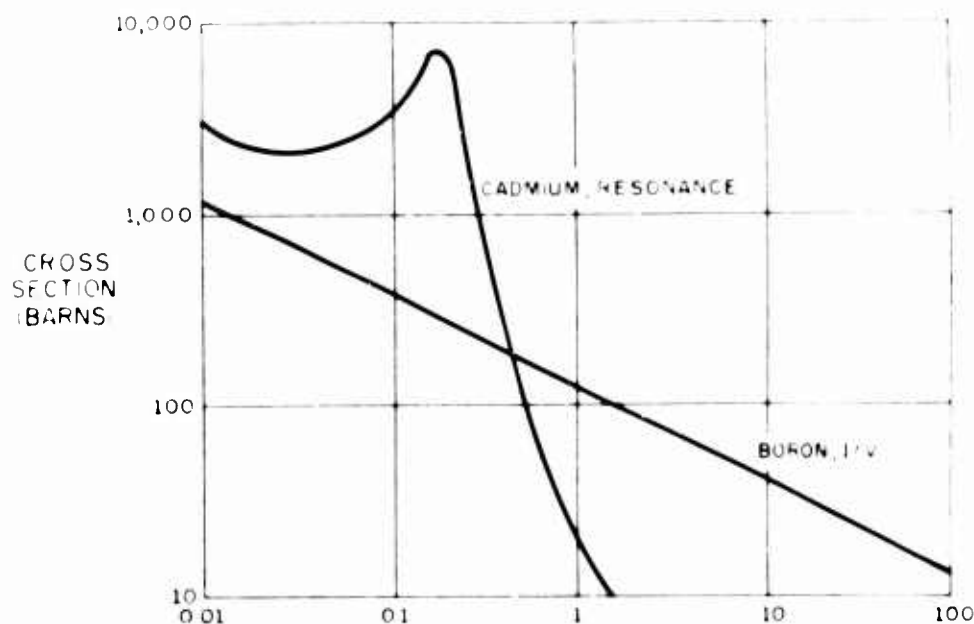
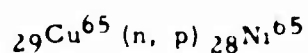
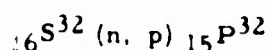
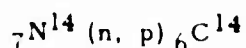
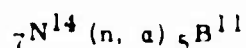


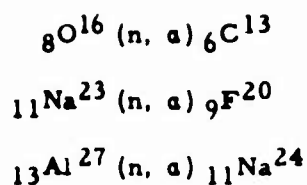
Figure 57. Cross Section for Boron and Cadmium

(2) (n, p) Reactions. Reactions of this variety and of the (n, d) can and do occur. The (n, d) reactions are generally less probable than the (n, p) reactions for slow neutrons. Examples of the (n, p) reactions are:

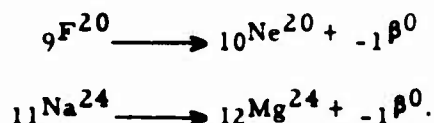


(3) (n,  $\alpha$ ) Reactions. The cross sections for some (n,  $\alpha$ ) reactions are fairly large for slow neutrons.  ${}^6_3\text{Li}^6 (n, \alpha) {}^3_1\text{H}^3$  can be used for a source of  ${}^3_1\text{H}^3$ .  ${}^{10}_5\text{B}^{10} (n, \alpha) {}^7_3\text{Li}^7$  is used for neutron detectors of the ionization chamber type. The reactions:





also occur. Many of the daughter nuclei are radioactive as:



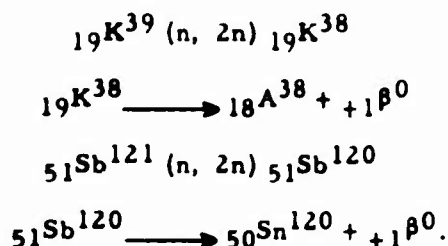
These are typical examples of neutron induced radioactivity.

(4) **Fission Reactions.** Probably the most important neutron reaction is the fission reaction. Fission is discussed in more detail in chapter 7. U-235 and Pu-239 both have large fission cross sections for slow neutrons. Cross sections for capture, scatter, and fission for U-235 are given in chapter 7. U-238 does not have an appreciable cross section for fission for neutrons of energy below 1 Mev.

c. **Fast Neutron Reactions.** The following group of reactions have reasonably large cross sections for fast neutrons.

(1) **(n, n) Reactions.** Here are grouped the elastic and inelastic scattering reactions. These particular reactions will be discussed in detail later.

(2) **(n, 2n) Reactions.** There are many cases in which the capture of a fast neutron has resulted in the emission of two neutrons. In most cases, the product nucleus is unstable. For example:



(3) **Fission.** Fast neutron fission occurs with U-238. The cross section for fission of U-238 is zero for low-energy neutrons, but gets very large for higher energy neutrons. Some fission will occur with neutrons down to 1 Mev energy.

d. **Variation of Capture Cross Section With Velocity.**

(1) The variation of capture cross section with velocity of the incident particle is, in general, inversely proportional to the velocity of the incident particle; that is, as the incident particle velocity increases, the capture cross section will decrease and vice versa. This rule can be expressed as:

$$\sigma \propto \frac{1}{V}.$$

It is a reasonably good rule which holds where  $V$  is the velocity of the incident particle over a great range of velocities. It is not a general law, in that many variations occur and the rule does not hold at very low velocities. The  $1/V$  relationship is a hyperbola, as in figure 58.

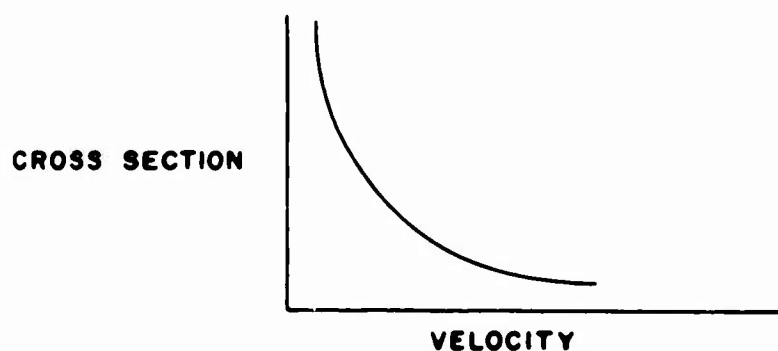


Figure 58.  $\sigma$  Versus  $V$

(2) The capture cross section for boron follows a  $1/V$  law quite well. The  $1/V$  law also applies reasonably well for slow neutron fissioning of U-235. For this reason, one would want to slow the 0.8 Mev neutrons ejected from a fission (process of moderation) in order to increase the cross section for using these neutrons to provide further fission.

(3) The  $1/V$  law definitely does not hold for fast neutron fissioning, nor does it hold even reasonably well for reactions other than capture and slow neutron fissioning.

#### c. Resonance Reactions.

(1) The  $1/V$  variation of capture cross section is a reasonably good rule. However, it sometimes breaks down at relatively low velocities where the cross section may suddenly rise sharply.

Figures 59 and 60 illustrate the capture cross section of cadmium and the total cross section of indium.

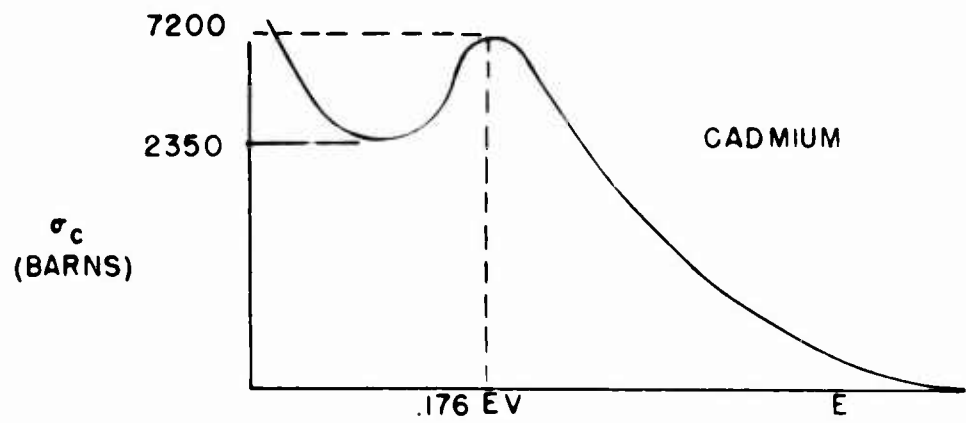


Figure 59. Capture Cross Section for Cadmium

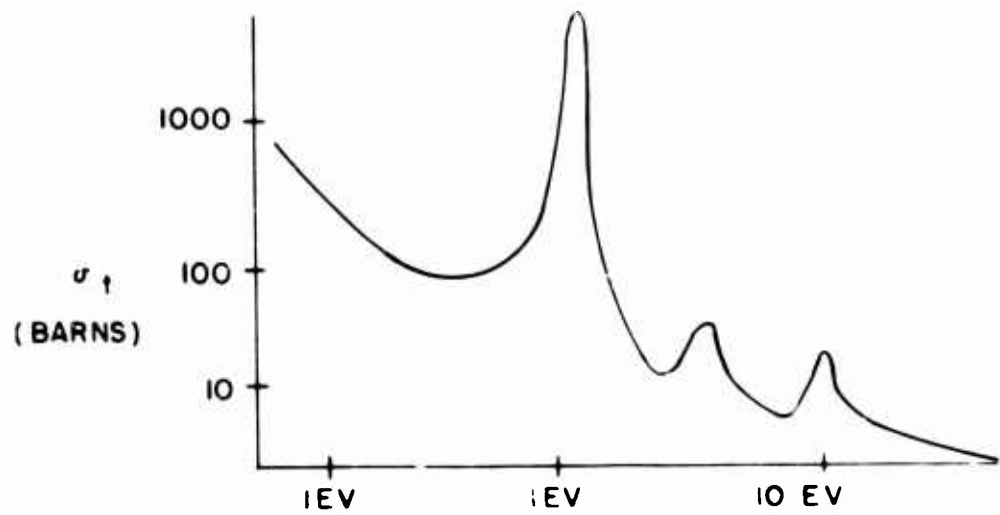


Figure 60. Total Cross Section for Indium

(2) Note that these rises of cross section (therefore, reaction probability increases) are very sharp. This means that at certain sharply defined energies, the reaction probability increases very rapidly. Note, also, that these sharp rises are superimposed on the  $1/V$  variation which is normally expected. The sharp rise in cross section at a particular energy is called a resonance. The reaction which occurs is the resonance reaction. The particular energy at which it occurs is the resonance energy.

(3) That resonance exists is a manifestation of the fact that nuclear energy levels are discrete. When resonance occurs, just the proper amount of energy is carried by the incoming particle to raise the compound nucleus to a higher energy level. Great use can be made of the resonance in reactions since it is possible to obtain far greater reaction probabilities by proper choice of the energy of the bombarding particles.

#### f. Scattering and Moderation.

(1) These are essentially (n, n) reactions. The need for moderation has been discussed in the preceding section.

(2) A moderator is a material which will slow neutrons down to the thermal energy range. What is wanted then is a material with a high-scatter cross section in which a great deal of the neutron momentum is transferred to the moderating material. To achieve high momentum transfer, one should use a very low mass number ( $A$ ) with a large density. The large density assures a small mean free path. It would be better to have inelastic collision rather than elastic collisions, since more energy would be lost per collision on the average. However, low mass number elements do not have large inelastic scatter cross sections. Even when using an ideal material, it would take a large number of collisions to slow fast neutrons down to thermal energy ranges.

(3) Good moderating materials are heavy water, graphite, and ordinary water. Liquid hydrogen and deuterium would be ideal except for the hazards involved in handling such materials.

(4) Another scattering reaction application is for the use of neutron reflectors. Neutron reflectors are used to keep extraneous loss of neutron populations from a given volume to a very low level. For this application, a material of large mass number ( $A$ ) is wanted in order to transfer very little of the neutron's momentum to the reflector. Again, a dense material is needed to keep the mean free path down.

(5) There is, however, an exception to the rule for reflector scattering. Beryllium has such a large elastic scatter cross section that momentum transfer is far outweighed in the final effect. Thus, beryllium is used for neutron reflectors.

## 129. NEUTRON DETECTORS

a. All neutron detectors are essentially secondary effect instruments; that is, they rely on a nuclear reaction to provide either charged particles or gamma radiation. This secondary radiation is measured. From this measurement, the number of neutrons can be determined.

b. Reactions which yield such emission are  $(n, \gamma)$ ,  $(n, p)$ ,  $(n, \alpha)$ , and  $(n, \text{fission})$ . The resulting particles are then detected by ionization chambers, Geiger counters, or scintillation detectors.

c.  $(n, \gamma)$  reactions are detected with Geiger counters or scintillation counters. Any of the detectors can be used for the other reactions.

d. An  $(n, \alpha)$  reaction very commonly used for detectors, particularly for ionization chambers is:



Commonly the chamber is filled with  $\text{BF}_3$  gas. The ionization in the chamber is caused by the emitted alpha particle.

e. Fission chambers are a rather common neutron detector. Here the dense ionization of the fission fragments produced by neutron induced fission can be easily measured in an ionization chamber.

f. The detection of fast neutrons presents a more difficult problem. Ideally, one would like to use a fission chamber with pure U-238; however, the cost is prohibitive. There is enough U-235 present in natural uranium to provide enough material for slow neutron fission.

g. The following scheme for detection of fast neutrons is used. An outside layer (several mean free paths of slow neutrons thick) of high-capture cross section for slow neutrons is used. This stops the slow neutrons but lets the fast neutrons through. The fast neutrons can then be slowed down and react in any of the systems mentioned above for thermal neutrons. The number of reactions then occurring is proportional to the original number of fast neutrons.

### 130. PROBLEMS

a. Boron has a capture cross section which has a  $1/V$  dependence. For 10 ev neutrons, the cross section is 30 barns. What will the cross section be for thermal neutrons (1/40 ev)?

b. Suppose Cd has a capture cross section that follows a  $1/V$  law.  $\sigma_c = 20$  barns for neutrons of 1 ev energies. What would the  $\sigma_c$  be for 0.2-ev neutrons? The resonance for capture occurs at 0.2 ev  $\sigma_c$  is actually 7000 barns. Compare this figure with your answer.



## **CHAPTER 7**

### **FISSION, FUSION, AND CHAIN REACTION**

#### **SECTION I. FISSION**

##### **131. HISTORICAL**

a. In the middle 1930's, many experimenters were using the newly discovered neutron to induce nuclear reactions. Particular interest was exhibited in bombarding the heavier nuclei with these particles. E. Fermi was particularly active in such work; and upon irradiating uranium with neutrons, he found several unknown  $\beta^-$  activities. These were believed to be transuranic elements, i. e., elements whose atomic number is greater than 92.

b. It was not until 1939 that the true nature of these  $\beta^-$  emitters was determined. Hahn and Strassman, repeating the experiments of Fermi, did very careful chemical analysis of the bombarded material. They found that some of the  $\beta^-$  activities were due to isotopes of barium and lanthanum.

c. It remained for L. Meitner, in conjunction with O. Frisch, to recognize the significance of these findings. They stated that when a neutron reacted with uranium, the heavy element "fissioned" or broke up into two nuclei of intermediate atomic number with the release of a large quantity of energy.

d. Later many physicists turned their attention toward this phenomenon, and a large amount of experimental data was obtained. Nier and Dunning showed that it was only the U-235 isotope that was fissioned by thermal neutrons. This agreed with the Bohr and Wheeler fission theory that had been published previously.

e. Considerable interest was aroused in the use of the fission process as a source of power when it was realized that the energy release per fission was of the order of hundreds of Mev. With the approach of World War II, a shroud of secrecy descended on much of the research in this field which hardly rose until the detonation of an atomic bomb at Hiroshima.

## 132. FISSION PROCESS

a. It is of interest to see just why we can get relatively large amounts of energy released during the fission process. Let us re-examine the curve originally presented in paragraph 88 showing the variation of binding energy per nucleon with atomic mass number  $A$ . Remembering that binding energy is really a negative energy, we can invert the curve to get a more graphic view of the relative stability of nuclei.

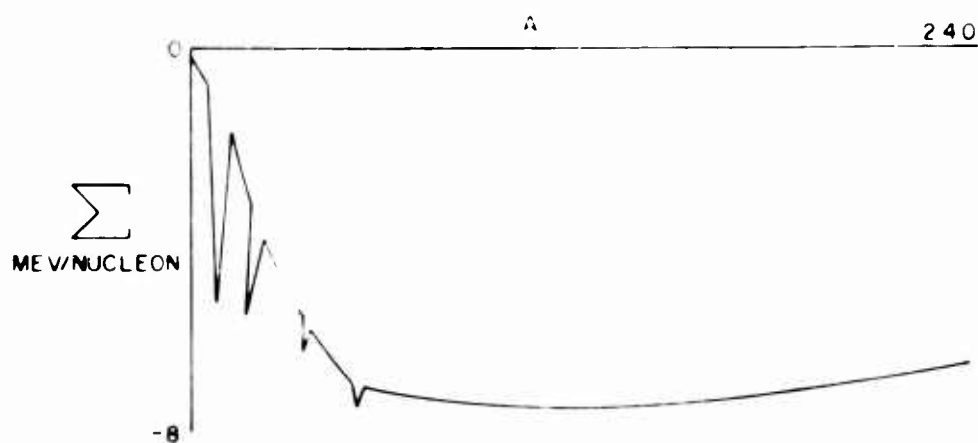


Figure 61. Binding Energy Per Nucleon

b. We can see that a nucleus of mass 240 has a binding energy of about -7.5 Mev/nucleon while one of mass 120 has -8.3 Mev/nucleon. Thus, if we could somehow get a heavy nucleus ( $A \sim 240$ ) to split into two lighter ones, we would have:  $(-7.5) - (-8.3)$  or 0.8 Mev/nucleon released as usable energy. Since there are 240 nucleons, the total energy released per split would be about 240 nucleons  $\times$  0.8 Mev/nucleon = 192 Mev.

c. This, then, is the process of fission; the splitting of a heavier nucleus into two or more lighter ones with resulting energy release. It should be noted that no whole nucleons are either created or converted into energy. Instead, only the average binding energy (or average mass) of the nucleons is changed; the large amount of energy released per reaction is due to the large number of nucleons involved.

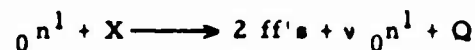
d. As mentioned previously, fission is often initiated by bombarding neutrons. Although it can occur in other ways, neutron induced fission is probably the most common.

e. Some interesting facts about the particles resulting from fission can be obtained by use of the  $n/p$  ratio. In chapter 4, it was mentioned that relatively stable nuclides with very large  $A$  have a value of about 1.5 for  $n/p$  while only about 1.3 for an  $A$  of 120. The products formed immediately after fission called fission fragments would have an  $n$ -to- $p$  ratio which is too high for their atomic mass and thus have an excess of neutrons. This tends to make them unstable, emitting  $\beta^-$  particles and, in some instances, neutrons.

### 133. THERMAL NEUTRON FISSION

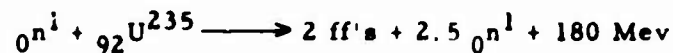
a. Although many nuclei can be fissioned in various ways, the main ones of interest are those that can be fissioned by thermal neutrons. These include:  ${}_{92}\text{U}^{233}$ ,  ${}_{92}\text{U}^{235}$ , and  ${}_{94}\text{Pu}^{239}$ .

b. The general equation for neutron fission may be written as follows:



where  $X$  is the fissionable nucleus, 2 ff's are the two fission fragments formed,  $\nu$  is the number of neutrons emitted upon fission, and  $Q$  is the energy released.

c. For thermal neutron fission of a  ${}_{92}\text{U}^{235}$ , we have:



d. The values of  $\nu$  and  $Q$  are average values. The nucleus will not always split in exactly the same way; and therefore, the number of neutrons given off as well as the exact nature of the fission fragment nuclei will vary. The best unclassified value of  $\nu$  for  ${}_{92}\text{U}^{235}$  is 2.5;  ${}_{94}\text{Pu}^{239}$  has  $\nu$  equal to 3.0. Both of these values are for fission induced by thermal neutrons.

### 134. INDUCING FISSION

a. Since energy is released upon fission and the fission fragments have a greater binding energy than the original nucleus, the fission reaction would be expected to go spontaneously, and to a small extent it does. However, it is usually necessary to excite the

fissionable nucleus, i. e. , give it a certain amount of extra energy, before it will fission. Thus, the original nucleus is relatively stable to fission in its ground state, but when excited beyond a certain point, it will fission readily.

b. The excitation energy may be given to the nucleus in many ways. One is to bombard it with high-energy photons. This causes photofission, and the minimum energy gamma that will produce this result gives an indication of the excitation energy required of different nuclei. See table 1.

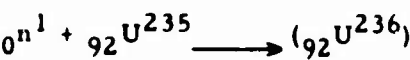
Table 1

<u>Nuclide</u>	<u>Photofission Threshold</u>
Th-230	5.40 Mev
U-233	5.18 Mev
U-235	5.31 Mev
U-239	5.08 Mev
Pu-239	5.31 Mev

c. Another means of producing fission is by striking a nucleus with high-energy charged particles such as very fast  $\alpha$  particles. This will result in inelastic scattering possibly exciting the nucleus enough to produce fission.

d. Neutron bombardment is the most common method of causing fission. Here the neutron is absorbed in the original nucleus forming a compound nucleus. Even if the neutron is in the thermal range and has little kinetic energy, the compound nucleus is highly excited due to binding energy of the neutron.

e. For example, the stable U-236 nucleus has a higher total binding energy (not per nucleon) than U-235. Therefore, a free neutron entering U-235 forms the compound nucleus which is excited by this difference in total binding energy. The following calculations show the net excitation energy assuming the kinetic energy of the original neutron is small:



Mass of n + Mass of U-235 - Mass of U-236 = Excitation Energy

$$1.00894 + 235.1133 - 236.11493 = 0.00731$$

$$= 931 \times 0.00731 = 6.8 \text{ Mev}$$

f. The actual energy required to initiate fission in U-235 is only about 5.3 Mev (table 1). In this case, the binding energy of the neutron alone is sufficient to cause fission. In other cases (e.g.,  $n + {}^{238}\text{U}$ ), the binding energy of the neutron is not large enough. However, if the entering particle has kinetic energy, this too goes to excite the nucleus. Therefore, the sum of the kinetic energy of the neutron plus its binding energy in the compound nucleus must be greater than the required activation (or threshold) energy to cause fission.

### 135. LIQUID DROP THEORY

a. The mechanism by which these heavy nuclei fission was propounded by Bohr and Wheeler using a liquid drop model. The collective behavior of all the nucleons can be approximated by considering the nucleus to be composed of an essentially incompressible fluid. The nucleus then acts like a drop of this fluid, the surface tension (due to nucleon-nucleon forces) tending to hold it together with the smallest area (spherical), and the coulombic forces (due to the protons) tending to break it up.

b. Normally, the nucleus is in its minimum energy level, i.e., spherical form. If it is excited by some means, it will start to oscillate through various shapes going first into ellipsoidal and then a "dumbbell" form, and if the energy is not sufficient, back again until the excess energy is given off, probably in the form of gamma rays. However, if the excitation is quite large, the dumbbell may neck down until the width is zero, at which time there are effectively two nuclei each positively charged which repel each other.



Figure 62. Liquid Drop Model of Fission

c. Calculations, using this model, agree quite well with experimental data.

d. The threshold energy required to produce fission may be calculated using the liquid drop model. These values and the excitation energy due to binding of a neutron are shown in the following table.

Table 2

<u>Target Nucleus</u>	<u>Compound Nucleus</u>	<u>Excitation Energy From Thermal Neutron</u>	<u>Required Threshold Energy</u>
U-233	(U-234)	6.6 Mev	4.6 Mev
U-235	(U-236)	6.4 Mev	5.3 Mev
U-238	(U-239)	4.9 Mev	5.5 Mev
Th-232	(Th-233)	5.1 Mev	6.5 Mev
Pa-231	(Pa-232)	5.4 Mev	5.0 Mev
Np-237	(Np-238)	5.0 Mev	4.2 Mev
Pu-239	(Pu-240)	6.4 Mev	4.0 Mev

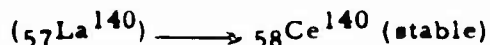
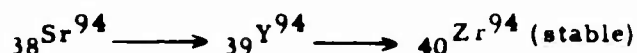
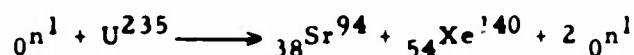
e. From the figures given in table 2, the possibility of neutron-induced fission can be ascertained. If the excitation due to binding of a neutron alone is greater than the required activation or threshold energy for fission, absorption of a neutron with no kinetic energy may produce fission. If, however, the threshold energy is the larger, it is necessary that the neutron have sufficient kinetic energy to make the total of neutron binding energy from absorption plus kinetic energy greater than the threshold energy for fission. This criteria and the data from table 2 show that all the target nuclei listed except U-238 and Th-232 can be fissioned by thermal neutrons. On the other hand, to fission U-238, a neutron whose kinetic energy is at least 5.5 - 4.9 0.6 Mev would be required.

### 136. FISSION PRODUCTS

a. The U-235 nucleus has been found to yield at least 30 different pairs of nuclides upon fission. The nuclei formed immediately upon fission are the fission fragments.

b. The fission fragments generally have too high an  $n/p$  ratio and usually emit  $\beta^-$  particles to decrease this ratio. The products of this radioactivity are often radioactive in the same fashion and tend to produce a chain of radioactive nuclides. These, including the initial fission fragments, are called fission products.

c. A typical fission and the resulting chain of fission products are shown below:



d. The probability of formation of a particular fission product from thermal neutron-induced fission is shown in figure 63. The probability in percentage of the occurrence of various products is plotted versus the mass number  $A$ . Since two nuclei are formed per fission, the summing of all the points on the curve would give 200 percent.

e. It is seen that there is a definite dip in the middle of the curves. These values represent the probability of symmetrical fission, i. e., where the two fission fragments are identical. This probability is very low, so it is evident that thermal neutrons normally cause asymmetrical fission.

f. As the energy of the fission causing neutron rises, so does the dip in the curve. With very high-energy neutrons, the curve would tend to have one maximum in the middle (due to asymmetrical fission).

### 137. NEUTRONS EMITTED

a. Since the  $n/p$  ratio in the products of fission is higher than that of stable nuclei, one would suspect that there is a possibility of neutron emission either during fission or by the fission products. This has proved to be the case.

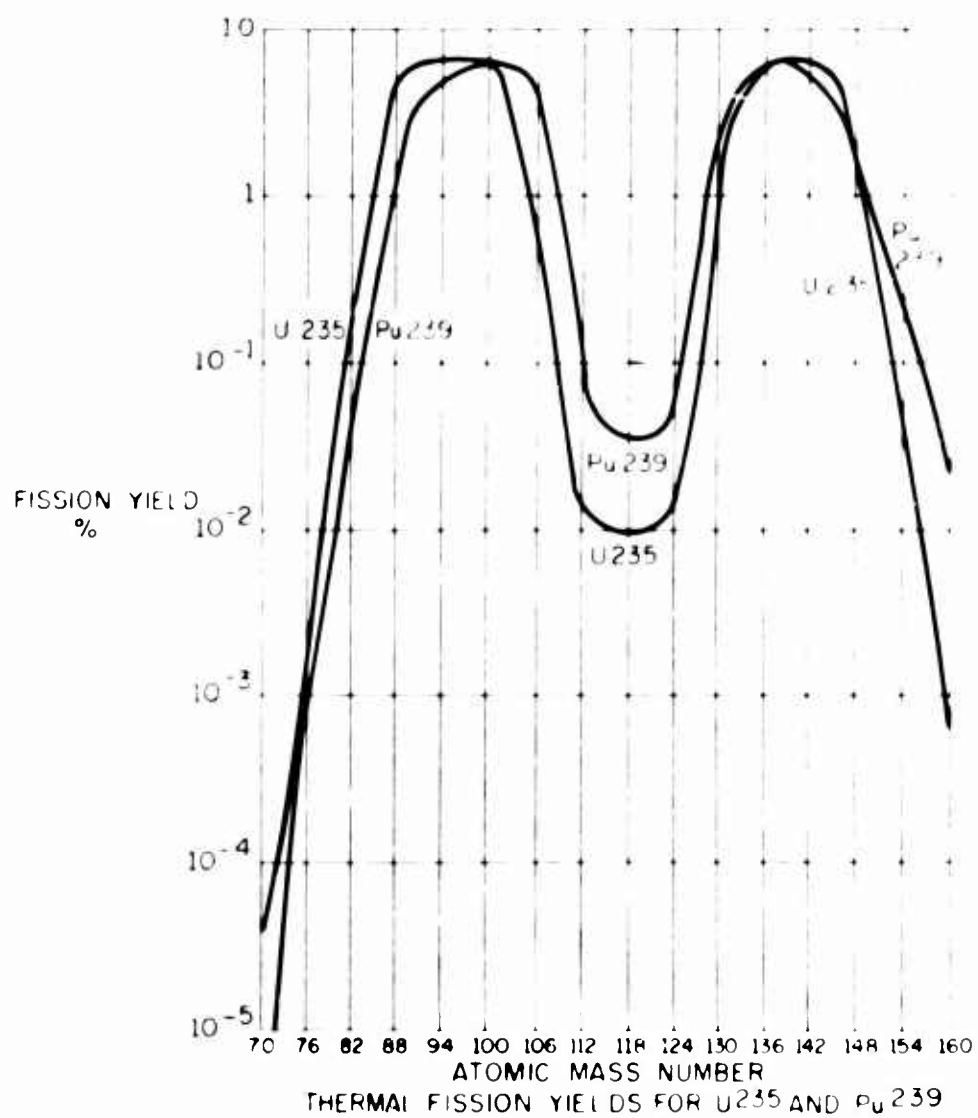


Figure 63. Thermal Fission Yields for U-235 and Pu-239



b. Most of the neutrons produced by the fission process are liberated immediately upon fission. In general, two or three neutrons are given off at this time. The exact number varies of course with the nature of the split that occurs (i. e., which fission fragments are formed). Average values for thermal neutron-induced fission for two materials have already been presented.

c. The energy of the neutrons given off in fission varies considerably. Most of them are in the fast range with a very small number even having energies of 12 Mev or higher. The average energy of the fission neutrons is 2 Mev while the most probable energy is about 0.8 Mev. The percentage of neutrons emitted with any particular energy is shown in figure 64.

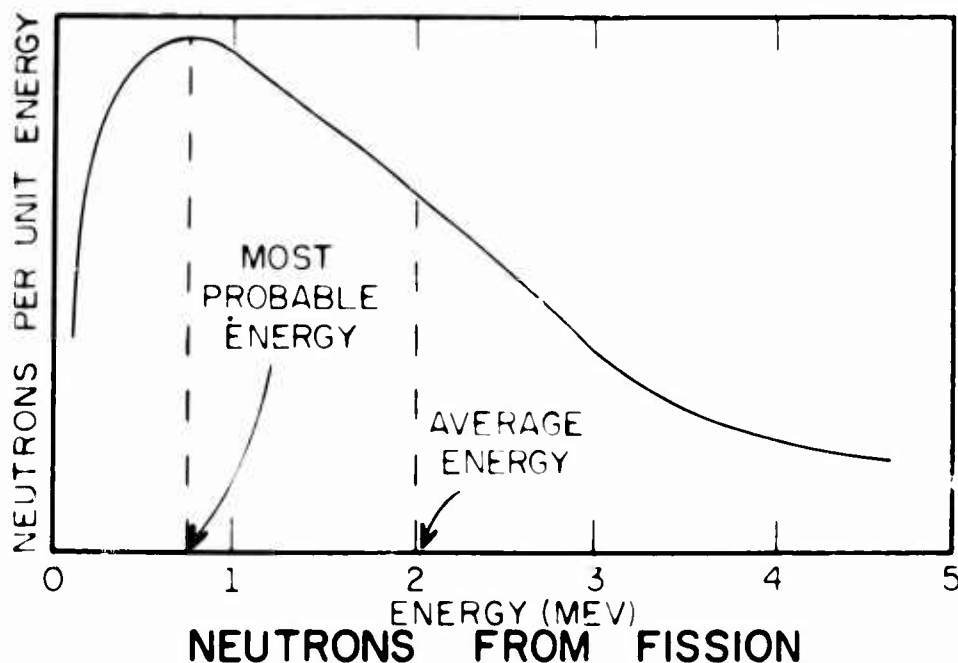


Figure 64. Neutrons From Fission

d. Neutrons that are emitted radioactively by the fission products are called delayed neutrons as compared to the prompt neutrons given during the fission process. These are less than 1 percent of the total number emitted and are given off at various times.

e. There are actually about six groups of delayed neutron emitters, and the number given off from each decays exponentially with time, the half lives varying from fractions of a second to almost a minute.

f. Although the number of delayed neutrons is small, they play a very important role in certain cases. This is particularly true in the control of nuclear reactors.

### 138. **ENERGETICS OF FISSION**

a. The total energy released due to fission may be calculated in the same way as the  $Q$  for any nuclear reaction once the manner of the split is known. Care must be taken to include, when desired, the energy of decay of the fission products. If the final stable fission products are used for calculations, all the decay energies will be included in the value of  $Q$ .

b. It is interesting to note the form in which the energy of fission release appears. Immediately after the split, the two highly charged fission fragments are in close proximity and repel each other greatly. Thus a large fraction of the total energy appears as kinetic energy of these fragments. Average values for the distribution of the total energy is shown in table 3.

Table 3    Energy Release in the Fission of U-235  
by Thermal Neutrons

Kinetic Energy of Heavy Fragment	65 Mev	
Kinetic Energy of Light Fragment	<u>100 Mev</u>	
Total Kinetic Energy of Fission Fragments		165 Mev
Kinetic Energy of Fission Neutrons		5 Mev
Prompt $\gamma$ -ray Energy		5 Mev
$\beta^-$ Decay Energy		5 Mev
$\gamma$ Decay Energy		5 Mev
Neutrino Energy		<u>11 Mev</u>
Total Energy Released		196 Mev

c. Most of this energy, especially the kinetic energy of the

fragments, eventually shows up as heat energy of the medium. Thus, the energy is distributed to the slower moving atoms, and the net effect is to raise the temperature. The greater the fraction of nuclei that fission, the higher is the temperature.

### 139. PROBABILITY OF FISSION

a. Spontaneous fission, that is without any outside cause, will occur in all fissionable nuclei, but its probability varies considerably for different nuclides. For any given nucleus, the rate of spontaneous fission follows the same type of exponential decay law as other radioactive phenomena. The half lives for various nuclides are shown in table 4. Also shown are the number of fissions that would occur, on the average, per minute per kilogram of pure material.

Table 4. Spontaneous Fission

<u>Nuclide</u>	<u>Half Life (years)</u>	<u>Fissions/kg/min</u>
U-233	$3.0 \times 10^{17}$	10
U-234	$1.6 \times 10^{16}$	190
U-235	$1.8 \times 10^{17}$	17
U-238	$8.0 \times 10^{15}$	380
Pu-239	$5.4 \times 10^{15}$	550
Pu-240	$1.2 \times 10^{11}$	$2.5 \times 10^7$

b. As in similar reactions, fission by neutrons may be expressed as the cross section of the nuclide in barns. The cross section will vary with the energy of the neutron, usually decreasing as the energy increases. Representative values are included in table 5.

Table 5. Thermal Neutron Cross Sections

<u>Nuclide</u>	<u><math>\sigma</math> Fission</u>	<u><math>\sigma</math> Scattering</u>	<u><math>\sigma</math> Capture (barns)</u>
U-235	549	8.2	101
U-238	0	8.2	2.8
Natural U	3.9	8.2	3.5
Pu-239	664	-	361

#### 140. PROBLEM

A certain fission process has the following equation:



If the atomic mass of  ${}_{50}^{134}\text{Sn}$  is 133.937 amu, how much energy is released?

### SECTION II. FUSION

#### 141. DEFINITION AND SOURCE OF ENERGY

a. Fusion is virtually the opposite of fission for it is the merger or fusion of two light nuclei into a heavier one with the release of energy. Fusion reactions are sometimes called thermonuclear reactions; the reason for this will be seen subsequently.

b. The source of energy released in fusion is the same as that for fission, a shifting or change in the huge forces that bind nucleons together. Again this is best seen on the curves of binding energy per nucleon and average mass per nucleon versus the mass number. See figure 61.

c. We can see that as  $A$  increases from 1 to 4, the binding energy decreases; that is, becomes more negative. Thus, if two nuclides with these small mass numbers are combined, the decrease in binding energy would show up as released energy.

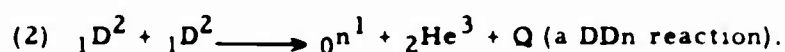
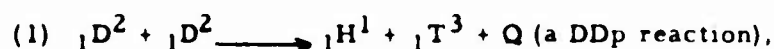
d. This also can be shown in the average mass per nucleon curve. See figure 26. Here it can be seen, the average mass per nucleon decreases as  $A$  increases from 1 to 4. Thus, if we combine two of these nuclei with no creation or destruction of whole nucleons, the mass of the new nucleus is less than the total mass of the initial nuclei. This loss in mass is released as the equivalent amount of energy.

#### 142. REACTIONS

a. Many different reactions may be actually classified as fusion reactions, but only a small number of these are of interest. In particular, we are interested in the reactions whose probabilities are fairly

large and which do not require too large an amount of energy to initiate them.

b. Since two nuclei that are to fuse must come extremely close to one another, it is necessary that there be a minimum electrostatic repulsion between them. For this reason, we are interested in nuclei having the minimum charge,  $Z = 1$ ; in other words, if a deuterium nucleus of sufficient energy strikes another deuterium nucleus, there is the possibility of two reactions.



When deuterium and tritium nuclei interact, the following reaction takes place:



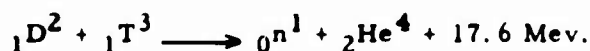
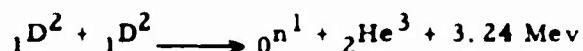
c. The values of  $Q$  may be obtained from the normal balance of masses. Thus, for the DDp reaction,

$$Q = (\text{Mass of } {}_1\text{D}^2) \times 2 - (\text{Mass of } {}_1\text{H}^1 + \text{Mass of } {}_1\text{T}^3)$$

$$= 2.01471 \times 2 - (1.00813 + 3.01702)$$

$$0.0427 \text{ amu} = 3.98 \text{ Mev.}$$

d. Doing similar calculations for the other reactions, the net results are:



e. The energy from these reactions will appear as kinetic energy of the products. The actual energy of the individual particle can be calculated from the law of conservation of momentum. Since there are just two final particles in each reaction, they must start off in opposite directions with equal momentums. Thus,

$$m_1 V_1 = m_2 V_2$$

where  $m_1$  = mass of particle 1

$m_2$  = mass of particle 2

$V_1$  = velocity of particle 1

$V_2$  = velocity of particle 2.

therefore,

$$\frac{V_1}{V_2} = \frac{m_2}{m_1}.$$

For the kinetic energies,

$$KE_1 = 1/2 m_1 V_1^2$$

$$KE_2 = 1/2 m_2 V_2^2.$$

The ratio of the kinetic energies is:

$$\frac{KE_1}{KE_2} = \frac{m_1 V_1^2}{m_2 V_2^2} = \frac{m_1}{m_2} \left( \frac{V_1}{V_2} \right)^2$$

But from the momentum formula,

$$\frac{V_1^2}{V_2^2} = \frac{m_2^2}{m_1^2}.$$

therefore,

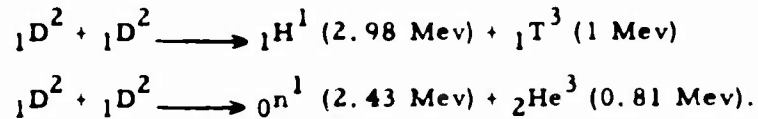
$$\frac{KE_1}{KE_2} = \frac{m_1 m_2^2}{m_2 m_1^2} = \frac{m_2}{m_1}.$$

This indicates that the total kinetic energy is distributed between the resultant particles in amounts inversely proportional to the masses of the resultant particles. This gives a simple means for determining the kinetic energy of these particles when the total kinetic energy is known.

f. Taking the DT reaction as an example, the total kinetic energy is 17.6 Mev. The mass of  ${}^4_2\text{He}$  is approximately 4, the mass of the neutron is approximately 1. Since the total mass of the resultant particles is approximately 5, about one-fifth (3.5 Mev) of the kinetic

energy is imparted to the helium atom, and the remaining four-fifths (14.1 Mev) goes to the neutron.

g. Making similar calculations for other reactions, the equations showing the kinetic energy of the product particles is as follows:



Most of the kinetic energy of the charged particles will be lost very rapidly through the ionization process. The neutron will also lose its energy in matter, but at a slower rate through scattering and other collisions.

### 143. PROBABILITY OF REACTION

a. As in all charged particle reactions, the probability of the occurrence of fusion in general depends on three things. These may be stated as:

(1) The probability that the two nuclei that are to react will collide at some point. In other words, they will be at the same place at the same time. This is often called the collision probability.

(2) The bombarding nucleus (it is convenient to speak of one nucleus at rest, as the target, and the other moving, as the bombarding nucleus) must be able to overcome the repulsive coulombic force of the target nucleus. To penetrate the "potential barrier," the bombarding nucleus may have enough energy to go over the top of the barrier. Even if its kinetic energy is not that great, there is still a finite probability of penetration of the barrier. This is due to the process called tunneling, where bombarding nuclei can figuratively tunnel through the barrier and appear in the nucleus. This process has already been considered in paragraph 96 on alpha decay.

b. The closer to the top of the potential barrier, the greater is the probability of tunneling. This is not a linear variation, and a small increase in kinetic energy may greatly increase the probability of barrier penetration.

c. Even though the two particles have collided and the potential barrier has been pierced, the particular nuclear reaction desired may not take place. The bombarding nucleus can pass right out again or a different, less favorable, reaction may occur. Thus, the probability of occurrence of the reaction of interest, once the penetration of the

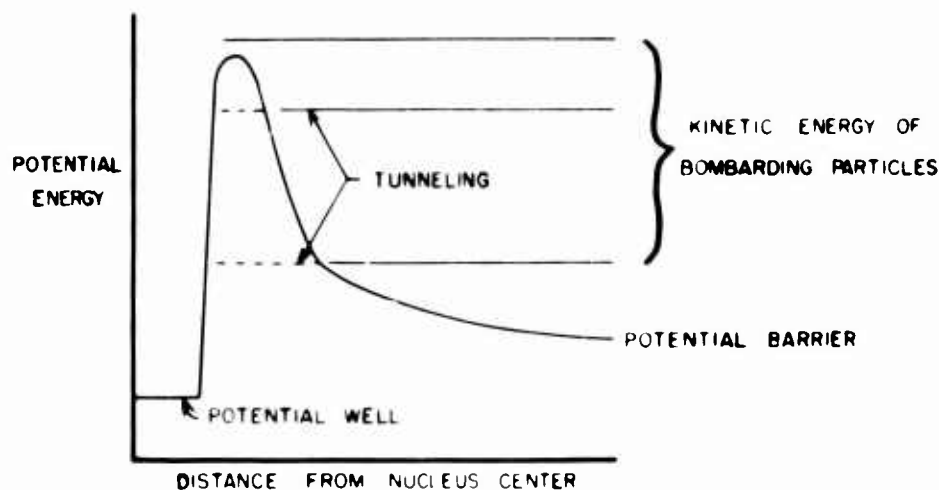


Figure 65. Potential Barrier and Tunneling

potential barrier has taken place, must be considered in determining the overall cross section or probability of the reaction.

d. The variation of the overall cross section for a particular reaction will vary considerably with the energy of the particles. This is due mainly to the change in probability of tunneling. For particles of relatively low kinetic energies, the chance of barrier penetration is so small that the reaction has an extremely small cross section.

e. The nuclei can be given sufficient kinetic energy to make barrier penetration more probable in two ways: through the use of particle accelerators, or by bringing the materials in question to a very high temperature (of the order of millions of degrees centigrade). The former method is only valid when a small number of reactions is desired, as accelerators can use only a limited number of particles. The latter system utilizes the thermal kinetic energy of nuclei in a high-temperature system, hence the term thermonuclear reactions.

f. Due to the high temperature of stars, stellar energy is produced by reactions of this type. The problem in a man-made system is how to raise the medium to the enormous temperature required and then contain it.

g. The cross sections of the fusion reactions have been



measured as a function of energy, and these values are presented in the two curves shown in figure 66. The DDn cross section was not plotted as it is almost the same as that for the DDp reaction.

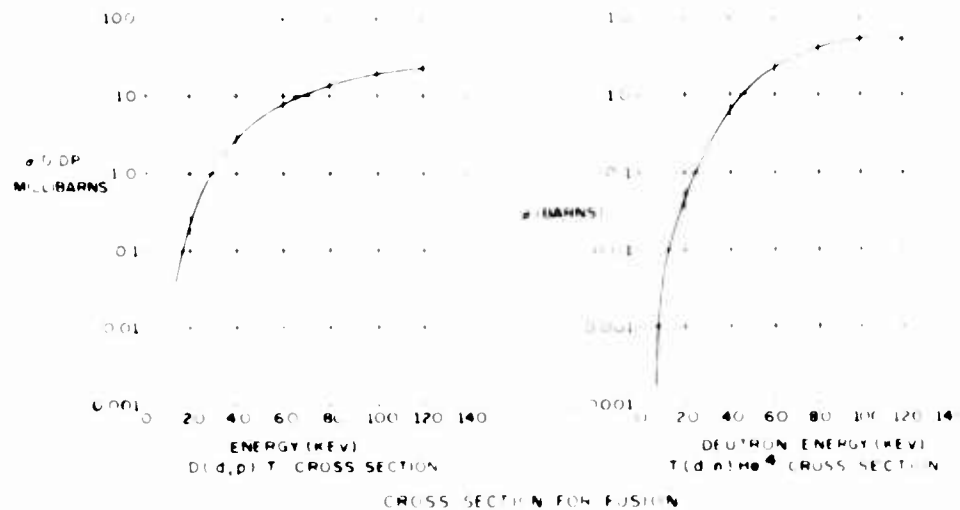


Figure 66. Cross Section for Fusion

h. In a mass of fusible material at high temperature, the kinetic energies of all the nuclei are not the same. Some sort of distribution, possibly a Maxwell distribution, is achieved; and the cross sections in the above curve would have to be averaged over the distribution.

#### 144. FUSION AND FISSION COMPARISON

Upon comparing fusion to the fission process, one notes certain differences:

a. Though fission releases much more energy per reaction, the energy release per mass of products is slightly greater in the fusion process.

b. In fusion, a large velocity, or kinetic energy, of the initial nuclei is usually required, while fission is usually initiated by neutrons.

c. The products of fission are usually highly radioactive; the products of fusion, aside from the long-lived tritium which is also consumed, are all stable.

### SECTION III. CHAIN REACTION AND CRITICALITY

#### 145. GENERAL

a. The possibility of production of great quantities of nuclear energy became possible upon the discovery of the fission reaction. However, as in most energy-producing reactions, something is required to initiate and to keep the reaction going.

b. In the combustion of wood in air, for example, heat or a high temperature is necessary to initiate and to keep up the reaction. This is true not only for the first part that ignites, but for all of the wood. Usually the energy produced by the initial burning heats up another part of the wood, enabling it to burn which, in turn, heats up some more of the wood, and so forth. Thus, a sort of chain develops where the heat produced by each section or part permits another section to burn and to supply more heat. This is the origin of the term chain reaction.<sup>1</sup>

c. In the fission process, heat is not required. Instead, neutrons are the links that form the chain. We have seen in paragraph 129 that neutron-induced fission is quite common and also that in the process of fission two or three neutrons are given off. If these fission-emitted neutrons can be used to initiate other fissions and new neutrons used to cause still other fissions, the chain will be built up. The goal is to produce energy, and this comes from fission. The neutrons are an indispensable byproduct if a large amount of energy and, hence, a large number of fissions are required.

d. Fission, however, is not the only reaction that neutrons can produce. Neutrons can be scattered, captured without producing a fission by the fissionable material, or captured by some additive or impurity in the active material without producing fission. These reactions have been discussed previously in chapter 6. Another possibility for the neutron is escape from the volume of active material, that is, it may go through the surface of the mass of fissionable material and be lost for further reactions in the fissionable material.

e. Thus, all these reactions compete with one another in any

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<sup>1</sup> A more general definition of a chain reaction is "a reaction in which one of the agents necessary to the reaction is itself produced by the reaction which causes like reactions."

volume of active material. The success of the chain reaction depends on the fraction of fission-formed neutrons that will produce other fissions.

f. We may speak of three broad classes of chain reactions. These are called nonsustaining, sustaining, or multiplying chain reactions (the terms convergent, stationary, and divergent, respectively, are often used).

g. We may think of an operating chain reaction as a series of generations, one right after the other. A number of neutrons produce fissions which produce neutrons, some of which will cause other fissions. The ratio of the number of second generation fissions to the number of first generation fissions may be called the multiplication or reproduction factor,  $k$ . This is the same as the ratio of the number of neutrons in the second generation that produce fissions to those in the first generation that caused fissions. The  $k$  factor will be the same for every generation, provided the material, geometry, etc., do not change.

h. If the multiplication factor is less than one, the number of neutrons in each generation is less than that in the previous one. Thus, if we start out with  $N_0$  neutrons, the

1st generation produces  $N_0$  neutrons  
2d generation produces  $k N_0$  neutrons  
3d generation produces  $k^2 N_0$  neutrons  
nth generation produces  $k^n N_0$  neutrons

i. With  $k$  less than one,  $k^n$  will be very small for large  $n$ , and hence, the chain reaction will tend to die out. This is a converging or nonsustaining chain reaction.

j. If  $k$  were exactly equal to one, the number of neutrons in each generation would be the same. Hence, the number of fissions per generation, or the number of fissions per unit time, since the lifetime of each generation of neutrons is approximately the same, would remain constant. This produces a chain reaction that is a constant power source and is required in the steady state operation of a nuclear reactor or pile. Such a system has a sustaining or stationary chain reaction.

k. A multiplying or divergent chain reaction has  $k$  greater than one. Hence, if you start with  $N_0$  neutrons, after  $n$  generations, there will be  $k^n N_0$  neutrons. The larger  $k$  is, the larger this number will be. Such a situation is required to increase the power rapidly and to

obtain a large energy release in a short period of time.

1. The type of chain reaction that will take place depends, among other things, upon the total mass of fissionable material present. If there is just enough mass to produce a sustaining chain reaction, there is a critical mass present. If less mass is present, a subcritical mass which will only maintain a nonsustaining chain reaction results. Finally a supercritical mass will support a multiplying chain reaction.

#### 146. INCREASING CRITICALITY

a. To increase the likelihood of a sustaining or multiplying chain reaction, minimize the reactions that compete with fission. This, of course, decreases the critical mass. Some of the means that may be used include the following:

(1) Purifying the material chemically to decrease the fraction of impurities that cause neutron capture, but do not fission.

(2) Enriching the fissile element in the isotope that fissions most efficiently and hence has less ordinary capture.

(3) Surrounding the active material with a good scattering medium which will reflect escaping neutrons back into the material.

(4) Using shapes with a minimum surface-to-volume ratio to reduce escape (a sphere is ideal).

(5) Increasing the density of the active material which also reduces the escape probability.

(6) Moderating the neutrons, i. e., slowing them down, which usually increases the fission cross section. This may be done by the inclusion of light-mass nuclei which scatter neutrons well, but this process takes considerable time and greatly slows down the reaction.

b. Also two subcritical masses could be brought together, i. e., addition of more mass. This, in general, reduces the probability of escape by decreasing the surface-to-volume ratio and tends to give a sustaining or multiplying chain reaction.

c. Figures 67, 68, and 69 graphically show a possible sequence of events in each type of chain reaction.

d. Figure 67 depicts a sample of uranium metal with impurities

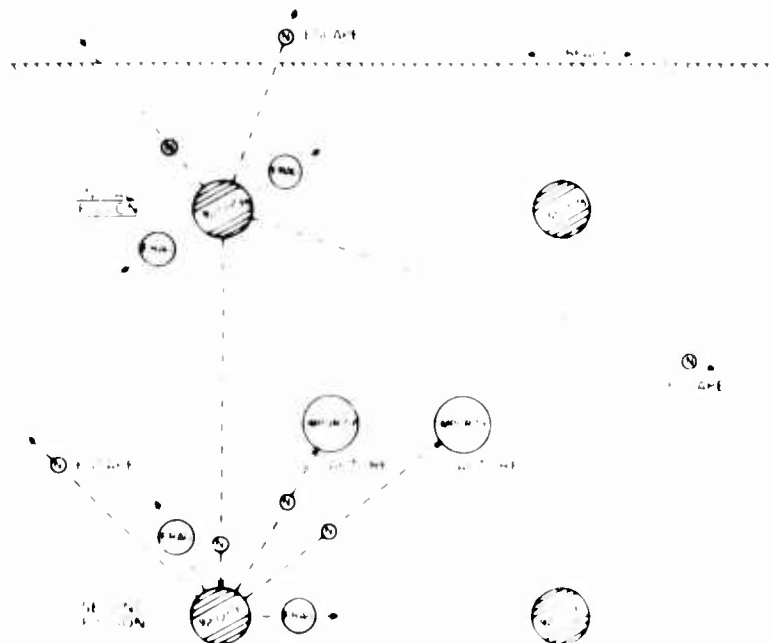


Figure 67. Nonsustaining Chain Reaction

capable of capturing neutrons. The initial fission produces 3 neutrons, 2 escape and 1 causes a second fission. The second fission produces 3 neutrons, 2 are captured, 1 escapes, and the chain reaction stops.

e. In figure 68, the initial fission yields 3 neutrons, 1 escapes, 1 is captured, and 1 causes a second fission. The second fission produces 3 neutrons; 2 escape and 1 causes a third fission. The third fission produces 2 neutrons; 1 escapes and 1 causes a fourth fission. The fourth fission yields 2 neutrons; 1 is captured and 1 causes a fifth fission. This example stresses that, on the average, the neutrons from 1 fission produce just 1 other fission, and the neutron population remains nearly constant.

f. In figure 69, note that fewer impurities reduce the number of neutrons lost by capture, and that closer spacing of the U-235 atoms reduces escape. On the average, two neutrons per fission cause more fissions, and the neutron population increases rapidly. (The fission fragments have been omitted from the drawing for clarity.)

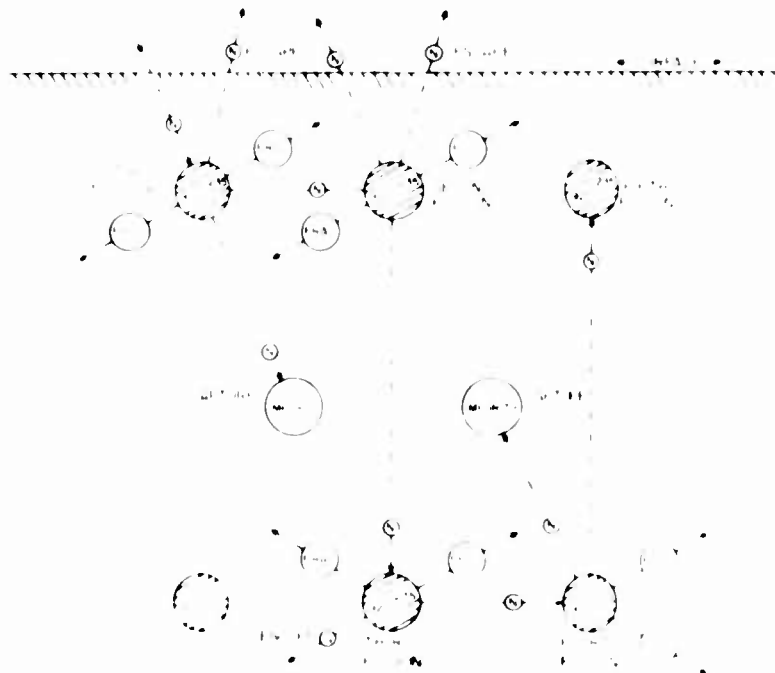


Figure 68. Sustaining Chain Reaction

#### 147. QUANTITATIVE TREATMENT OF CRITICALITY

a. So far, the problem of criticality has been examined qualitatively. It is now necessary to examine some simple calculations. Even here, the problem will be greatly simplified by using certain assumptions. If a more complete picture is desired, the reader should seek one or more of the advanced texts on this subject.<sup>1</sup>

b. In the treatment that follows, it is assumed that there are no chemical impurities in the active material that absorbs neutrons. This, of course, is never completely true, but this discrepancy could be corrected by adjusting upward the capture cross section of the fuel.

(1) If the mass of the active material is assumed to be infinite in volume, the problem of escape is eliminated (no neutrons could leave an infinite volume). The problem here is to determine how well

<sup>1</sup> Elements of Nuclear Reactor Theory, Glasstone and Leland.

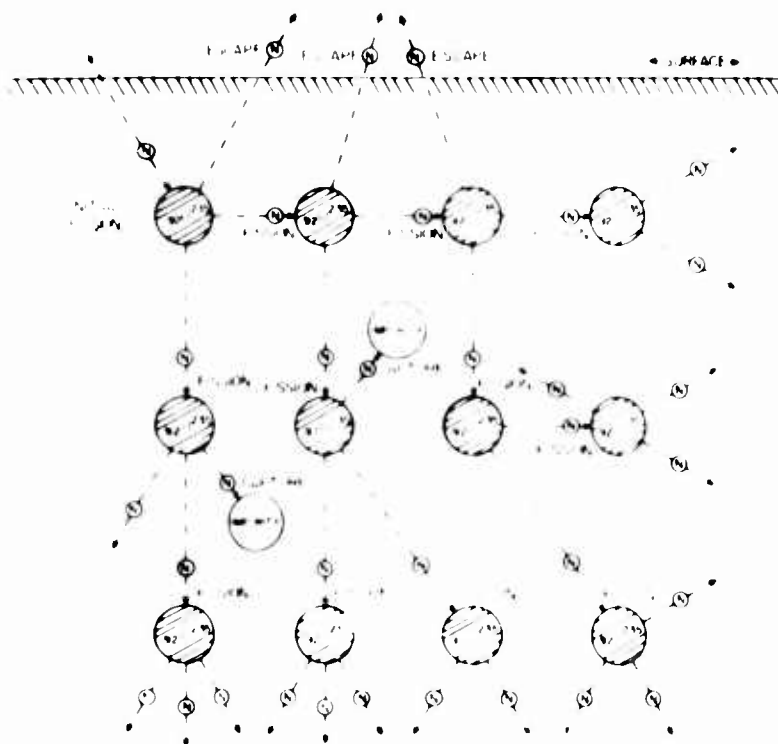


Figure 69. Multiplying Chain Reaction

the fission reaction competes with other nuclear reactions in utilizing the free neutrons in the material. There are three possibilities for any neutrons in an infinite medium: capture, scatter, or fission. These, in turn, have their respective probabilities of occurrence or cross section:  $\sigma_c$ ,  $\sigma_s$ ,  $\sigma_f$ . The total cross section is:

$$\sigma_t = \sigma_c + \sigma_s + \sigma_f.$$

Whenever a neutron undergoes capture, it is lost completely; in the scattering process, no neutrons are lost, but none are gained. In fission, one neutron is swallowed up. If  $\nu$  is the number of neutrons released in the fission process, there is a gain of  $(\nu - 1)$  neutrons. The net gain of neutrons per collision is equal to the sum of the probabilities of each reaction per collision times the number of neutrons gained or lost for that type reaction.

For capture,

$$\frac{\sigma c}{\sigma T} = \text{fraction of captures per collision}$$

$$-1 = \text{net gain of neutrons per capture}$$

$$-1 \times \frac{\sigma c}{\sigma T} = -\frac{\sigma c}{\sigma T} = \text{net gain of neutrons from capture per collision.}$$

For scatter,

$$\frac{\sigma s}{\sigma T} = \text{fraction of scatters per collision}$$

$$0 = \text{net gain of neutrons per scatter}$$

$$0 \times \frac{\sigma s}{\sigma T} = 0 = \text{net gain of neutrons per collision from scatter.}$$

For fission,

$$\frac{\sigma f}{\sigma T} = \text{fraction of fissions per collision}$$

$$(v - 1) = \text{net gain of neutrons per fission}$$

$$\frac{\sigma f}{\sigma T} (v - 1) = \text{net gain of neutrons per collision from fission.}$$

The sum of the equations is:

$$\begin{aligned} \text{Net gain of neutrons per collision} &= \frac{\sigma f}{\sigma T} (v - 1) + 0 - \frac{\sigma c}{\sigma T} \\ &= \frac{\sigma f (v - 1) - \sigma c}{\sigma T} \end{aligned}$$

This net gain of neutrons per collision may be called the productivity factor,  $f$ . It is, of course, directly related to the multiplication factor,  $k$ . This relationship will be discussed later. We can now determine what materials can support the different types of chain reactions by using the above equation and experimental cross sections and  $v$  values presented in section I. If  $f$  is equal to zero, there is no gain or loss of neutrons per collision, a just critical system would result. If  $f$  were greater than zero, a supercritical reaction would result, and, if less than zero, a subcritical system. It should be borne in mind



that this is still for an infinite medium with no neutron escape. Consider a system composed only of  ${}_{92}\text{U}^{235}$  and a moderating medium that causes all the fission-born neutrons to be thermalized very quickly without capture. The thermal absorption, scatter cross section, and  $\sigma f$  values for  ${}_{92}\text{U}^{235}$  are:

$$\sigma f = 549\text{b}$$

$$\sigma s = 8.2\text{b}$$

$$\sigma c = 101\text{b}$$

$$\nu = 2.5$$

Therefore,

$$f = \frac{549(2.5 - 1) - 101}{658}$$

$$1.1$$

Since  $f$  is greater than zero, it is possible for  ${}_{92}\text{U}^{235}$  to be in a supercritical state or to sustain a multiplying neutron chain reaction. If it were desired to have  ${}_{92}\text{U}^{235}$  in a just critical state, a finite volume could be used to allow some escape of extraneous neutrons or absorbers added to increase the effective  $\sigma c$  and thus reduce  $f$ . Compare the productivity factor,  $f$ , to the multiplication factor,  $k$ .

$f$  = number of neutrons gained per collision (fission, capture, and scattering)

$k$  = number of neutrons produced per absorption (fission or capture)

$$\frac{\text{The number of collisions}}{\text{The number of absorptions}} = \frac{\sigma c + \sigma s + \sigma f}{\sigma c + \sigma f} = \frac{\sigma T}{\sigma T - \sigma s}$$

Therefore,

$$f \times \frac{\sigma T}{\sigma T - \sigma s} = \text{number of neutrons gained per absorption.}$$

If the number of neutrons gained per absorption equals the number of neutrons produced per absorption - 1, then

$$f \frac{\sigma T}{\sigma T - \sigma s} = \text{number of neutrons produced per absorption} - 1$$

$$= k - 1$$

$$\text{or, } f = (k - 1) \frac{\sigma T - \sigma s}{\sigma T}$$

$$\text{or, } k = 1 + f \frac{\sigma T}{\sigma T - \sigma s}$$

Since this is for an infinite medium,  $k_{\infty}$  is used.

$$k_{\infty} = 1 + f \frac{\sigma T}{\sigma T - \sigma s}$$

If  $\sigma s$  is small compared to  $\sigma T$ ,  $k_{\infty} = 1 + f$ .

In calculating  $f$  and  $k_{\infty}$ , it is necessary to use accurate values of the cross sections and  $v$ . To do this, consider the energy spectrum of the neutrons and the variation of cross section with energy. This is a very difficult problem. The text shall merely concern itself with average values (as in the preceding calculation of  $f$ ) which, unfortunately, will not fit every situation.

(2) In a finite medium, there is a definite possibility that neutrons may leave the active material and not return. This must be considered in determining how much of a fissionable material in a given shape is required for a critical mass. To calculate accurately the effect of leakage, equations must be set up to follow the neutrons during their diffusion (i. e., scattering) throughout the medium. Consideration must be given to any moderation used during the process preceding diffusion. A detailed treatment of this subject is considered beyond the scope of this book.

#### 148. MULTIPLICATION

a. A term frequently encountered is multiplication,  $M$ . This refers only to subcritical systems and may best be defined as the number of neutrons present at a point in a medium containing a source and fissile material divided by the number of neutrons at the same point from the source if no fissile material is present.

b. If a source of neutrons is placed in a medium containing no fissionable material, there will be a certain distribution of neutrons throughout the medium. If some fissionable material is now added to the medium, there will be an increase in the neutron density. There will still be the source neutrons, but some nuclei will fission forming new neutrons causing new fissions, etc. Thus, a nonsustaining chain reaction results; but as the initial neutron source is always present, neutrons from an effectively infinite number of generations are produced.

c. If  $S$  is the number of source neutrons emitted per unit time, there will be  $Sk$  neutrons in the first generation,  $Sk^2$  in the second, etc. Here again,  $k$  is the multiplication factor, and since this applies only to subcritical masses,  $k$  is less than one. Therefore,

$$M = \frac{S + kS + k^2S + \dots + k^rS + \dots}{S}$$

$$= 1 + k + k^2 + \dots + k^r + \dots$$

By the binomial theorem,

$$M = \frac{1}{1 - k}.$$

d. We can see that as  $k$  approaches one,  $M$  approaches infinity. Therefore, it is possible to have a very large multiplication from a barely subcritical mass. Since there is always some neutron source present (cosmic rays or spontaneous fission), it is possible to have large neutron fluxes even from a subcritical system.

#### 149. KINETICS

a. Something should be said of the kinetics of a neutron chain reaction. That is: At what rate does the neutron density or fission rate build up or decrease in a given medium?

b. Actually, this is a highly complex problem especially if  $k$  is approximately one. This comes about from the five or six groups of delayed neutrons which are not given off immediately upon fission. These tend to slow down the fluctuations of the reaction.

c. If  $k$  is exactly equal to one, the fission rate, power, and neutron density will remain constant with time (except for statistical fluctuations). If  $k$  is considerably greater than one, the effects of delayed neutrons due to their relatively small numbers may be neglected. This is even more valid if times much shorter than the half life emission time of the delayed neutrons is considered.

d. Let  $\tau$  be the mean generation time for neutrons. This is the mean time between the birth of one fission neutron and its fathering another neutron by causing a fission. Remember that a neutron chain reaction is a statistical process. Not all neutrons travel the same distance or for the same time before a collision, but averages may be used. All the neutrons in a generation do not start out at the same time. There is not a sudden burst of fissions at the start of a

generation, the fissions occur fairly uniformly throughout the generation. Let  $N$  be the number of neutrons in the first generation and  $N + dN$  the number in the second. If  $k$  is the multiplication factor, then

$$\frac{N + dN}{N} = k$$

$$\text{or} \quad \frac{dN}{N} = k - 1$$

$$\text{and} \quad dN = N (k - 1).$$

The time rate of change of the number of neutrons is  $\frac{dN}{dt}$ ; and since the time each generation requires is  $\tau$ ,

$$\frac{dN}{dt} = \frac{N}{\tau} (k - 1).$$

Assuming  $k$  and  $\tau$  remain constant, integrate this expression to find the number of neutrons at any time,  $t$ . At  $t = 0$ , there were  $N_0$  neutrons.

$$\frac{dN}{N} = \frac{(k - 1)}{\tau} dt$$

$$\int_{N_0}^N \frac{dN}{N} = \frac{(k - 1)}{\tau} \int_0^t dt$$

$$\ln\left(\frac{N}{N_0}\right) = \frac{(k - 1)}{\tau} t$$

$$\text{or,} \quad N = N_0 e^{\left(\frac{k - 1}{\tau}\right) t}$$

Since the number of fissions in such a case is directly proportional to the number of neutrons, this equation also demonstrates how energy rate or power varies with time. The term

$$\frac{(k - 1)}{\tau}$$

is sometimes called the neutron growth rate or alpha.

## 150. SUMMARY

a. Due to the necessity of having a fairly simple presentation, many shortcuts and oversimplifications have been made here in studying the statics (criticality) and kinetics of neutron chain reactions. However, even the best quantitative treatments have not completely solved the problem. This is partly due to the microscopic nuclear data not being as complete as desired and also to the great complexities inherent in the calculations for any given system.

b. For these reasons, the best way to obtain information on a given system is to perform macroscopic experiments on the system itself, that is, for a certain type of active material, start out with a subcritical mass of it and add more in small increments. Then, determine exactly how much of the fissionable material is required for a critical mass. This is called a critical experiment.

c. Similarly, kinetic experiments can be conducted to get information on particular systems. Even here though, the quantitative calculations are extremely important. They not only tell the range in which to perform the experiment, but also allow the necessary interpolations and extrapolations to be made in going from one system to another. This greatly reduces the number of necessary experiments.

## **CHAPTER 8**

### **HEALTH PHYSICS**

#### **151. INTRODUCTION**

An important problem confronting personnel working with radioactive materials is the avoidance of personal harm from the adverse biological effects of nuclear radiations. Concern exists not only for the danger of illness and possible death, but also for the occurrence of undesirable mutations among the offspring of radiation victims. The following discussion will briefly review the characteristics of various types of radiation, then will describe the basic components of the human body, specific effects of radiation on these components, symptoms and treatment of radiation overexposure, and lastly will describe various means of reducing and controlling radiation intensity.

#### **152. PARTICLES AND THEIR RANGE**

a. Alpha particles are positively charged helium nuclei. They lose energy rapidly in producing dense ionization and are consequently short-ranged. This range for most alpha particles is less than 10 centimeters in air and less than 100 microns in animal tissue. Alpha emitters, when permitted to become lodged within the human body, are serious health hazards; externally, however, inability of the alphas to penetrate the dead layer of skin renders them virtually harmless, assuming the dead skin layer is unbroken.

b. Beta particles are high-speed electrons emitted from a nucleus. They produce relatively sparse ionization and have proportionately greater range in comparison with alpha particles. This range is from several meters in air to about three centimeters in animal tissue. A possible health hazard exists from external beta emitters, since their ability to penetrate body tissue is significant; beta emitters lodged within the human body are also hazardous because essentially all their energy is absorbed by the body through ionization.

c. Neutrons are neutral particles with low probability for direct ionization of matter. These particles, nevertheless, present a health hazard due to secondary ionization by the products of neutron interaction with matter. As neutrons pass through animal tissue, their

collisions with nuclei cause protons or alpha particles to be ejected; these particles then produce direct ionization.

d. Gamma rays are electromagnetic radiations with neither charge nor mass. They lose energy primarily by Compton scattering and the photoelectric effect in passing through animal tissue. Gamma emitters external to the body present a definite danger due to their great penetrating ability. Remarks in this section concerning gamma radiation apply also to X-radiation.

e. Protons are positively charged hydrogen nuclei. Their behavior is similar to that exhibited by alpha particles due to charge and mass similarities.

f. Relative Ionization and Range. The relative ionization density and range of the respective radiations are presented in table 7.

Table 7. Relative Ionization

<u>Particle</u>	<u>Relative Ionization</u>	<u>Range in Air</u>	<u>Range in Tissue</u>
Gamma	1	Finite	Finite
Beta	100	3 to 7 meters	Less than 3 centimeters
Alpha	10,000	3 to 10 centimeters	0.01 to 0.10 centimeters
Neutron	0	100's of meters	10 centimeters
Proton	1,000	--	--

The gamma radiation range in air and tissue is listed as finite. Since gamma attenuation is an exponential function, absolute numerical range limitations can not be specifically assigned.

g. Mechanisms of Radiation Exposure. Personnel employed in the handling of radioactive substances must recognize the two basic mechanisms of radiation exposure: first, there may be radiation external to the body directly from a source, contamination outside the source container, or contamination on the person or clothing of the worker; second, there may be internal radiation from material collected through inhalation, ingestion, or absorption through the skin. Unnecessary exposure to any type of radiation is to be avoided.

#### 153. THE HUMAN BODY

a. The human body is composed of the following components, here arranged in order of increasing subdivision: systems, organs, tissue, and cells. An example of this arrangement is: the respiratory system, lungs, lung tissue, and cells of the lung tissue. A specific type of tissue may occur in many different organs. Also, each specific type of tissue is composed of cells peculiar to that tissue.

b. Cell response determines radiation effects on a given tissue, which subsequently determines effects on the organ and system concerned. For example, radiation damage to the cells of the stomach or intestine could result in nausea or vomiting. Symptoms are visible effects occurring due to malfunction of a system and directly reflect cellular damage.

#### 154. CELL COMPOSITION AND RESPONSE TO RADIATION

a. Composition and Function. All cells with exception of the red cells in the blood, have the following common components: cell membrane, cytoplasm, nuclear membrane, and nucleus.

(1) The cell membrane completely encloses the cell and is semipermeable to permit passage of nutritional materials into the cell and passage of waste materials out of the cell. Permeability of the membrane may be either impaired or improved by the influence of radiation.

(2) The cytoplasm comprises the bulk of the cell and is composed of water, fats, proteins, etc. Also contained in the cytoplasm are biological catalysts called enzymes, which control the chemical changes by which energy is provided for body processes and activities. Normally, this process, called metabolism, is not significantly affected by radiation.

(3) The nuclear membrane surrounds the nucleus within the cell and is similar to the cell membrane. Its composition and functions are presumably very similar to those of the cell membrane.

(4) The nucleus is the governing body of the cell and is the part most sensitive to radiation. It is composed almost entirely of protein. Radiation effects on the nucleus are determined by the relative activity of the nucleus at the time of irradiation; that is, the stage achieved by the nucleus in the process of division. The cells most susceptible to radiation damage then are those which divide most rapidly. On this basis, radiosensitivity can be classified as follows: most sensitive - bone marrow, lymph glands, lining of mouth and intestines, hair follicles, and skin; moderately sensitive - liver and



kidney tissue; least sensitive - nerve, brain, and muscle tissue.

b. Response to Radiation. Irradiation of a cell can cause damage to components of the nucleus-controlling characteristics of daughter cells, resulting in the production of so-called mutations. The probability that such mutations may ultimately be manifested in the appearance of offspring with characteristics radically different from those of the parents is only about one in 10,000 for maximum sublethal radiation doses. This probability is not significantly different from the probability for natural occurrence of mutations. Since greater mutation probabilities would involve lethal radiation doses, they need not be considered.

#### 155. UNITS

a. Biological definitions for radiation units are unique in the sense that biological effects are determined by the absorption of energy in tissue and not simply by the amount of energy passing through the tissue. For example, a beam of high-energy gamma rays is quite penetrating and may produce fewer biological effects per unit of tissue than less penetrating, low-energy gamma rays with the same total energy flux.

b. The roentgen (r) is defined as that amount of X- or gamma-radiation required to produce by ionization 1 electrostatic unit of charge in 1 cubic centimeter of dry air at standard temperature and pressure. Combining this definition with certain experimental observations permits the establishment of more useful units. One roentgen is equivalent to:

(1)  $2.08 \times 10^9$  ion pairs per cubic centimeter of air at standard temperature and pressure, or

(2)  $1.16 \times 10^{12}$  ion pairs per gram of air at standard temperature and pressure, or

(3)  $6.97 \times 10^4$  Mev per cubic centimeter of air at standard temperature and pressure, or

(4)  $5.37 \times 10^7$  Mev per gram of air at standard temperature and pressure, or

(5) 86 ergs per gram of air at standard temperature and pressure.

The biological effects of high-energy radiation are much more

profound than might be expected from the total energy absorbed. The absorption of 1000 roentgens of radiation by the whole body would almost certainly be fatal; however, the total temperature rise due to the absorbed energy would be only  $0.002^{\circ}\text{C}$ . and only about 2 atoms out of  $10^8$  would be ionized.

c. Because alpha and beta particles do not ionize in the same manner as do gamma and X-rays, the definition of the roentgen cannot be meaningfully extended to the measurement of alpha and beta ionization effects. For this reason an alternate unit is introduced called the roentgen equivalent physical (rep).

(1) A rep is the amount of ionizing radiation required to produce 97 ergs of energy in one gram of tissue.

(2) It turns out that the production of  $1.60 \times 10^{12}$  ion pairs in a gram of air at standard temperature and pressure results in heat liberation of 86 ergs from the loss of 33.5 ev per ion pair formed. Therefore, the average ionization in tissue takes a little more energy than in air.

(3) Unfortunately it turns out that the biological effect of radiation does not always depend directly upon the amount of energy absorbed. This makes it necessary to introduce a new unit called the roentgen equivalent man, (rem).

(4) A rem is the amount of radiation of any kind that will produce an effect equivalent to that produced by the absorption of one roentgen of X- or gamma radiation.

(5) Application of this unit is handicapped by differences among radiations in relative effectiveness, depending upon such things as the biological effect chosen for observation or the energy of the ionizing particle or photon.

d. A relatively new unit of measurement coming into current use is the rad, standing for radiation absorbed dose.

(1) One rad is equal to 100 ergs per gram of material.

(2) This applies for all materials, whether they be steel, sand, water, bone, or soft tissue. This unit has the advantage of being an energy per unit mass, so that one need know in addition to the rads only the mass of the material to calculate the total energy absorbed. Whenever the rad is used, the type of material should be specified. Formerly there was very little information available on the absorbing

power of different materials. Take for example air and tissue. A rad in air is equivalent to 100 ergs per gram. But a roentgen in air is equivalent to 86 ergs per gram. So in air one roentgen is equal to  $86/100 = .86$  rad. However, in soft tissue one roentgen is equivalent to 97 ergs per gram; but a rad is still 100 ergs per gram. Then in tissue 1 r corresponds to  $97/100 = .97$  rad. The conversion factors from roentgens to rads are not the same for air and soft tissue because the absorption characteristics of these materials differ.

e. Since equal amounts of two or more types of radiations, measured in ergs/gm, may have different biological effects it is necessary to introduce a term called the relative biological effectiveness (RBE). For instance 200 rad of gamma radiation in the eye would be much less likely to produce cataracts than would 200 rad of neutron radiation. Actually the RBE is a dimensionless number, since it is the ratio of the effectiveness of one type of radiation compared to gamma in producing biological effects. Although the particular biological effect chosen for observation is not always stated in tables, it really ought to be so stated. The RBE may also vary with the energy of the radiation (ie, fast neutrons may be more effective in producing damage than slow neutrons). The dose in rems is directly calculable when both the dose in rads and the RBE are known. Since rems reflect the biological effect, RBE the efficiency of a given type of radiation, and rads the amount of energy per gram of material rems are given by:

$$\text{rems} = \text{RBE} \times \text{rads}$$

Moreover, the effects of different kinds of radiation can be added once converted into rems because a rem of one type radiation is equal to a rem of any other type radiation. If we receive a radiation dose from several sources of radiation, the dose can be computed by adding the rems received from each type.

f. Relationship of radiation units. Table 8 gives the relationships among r, rep, rem, and rad for several different radiations and materials. Remember that a rem of one type of radiation is biologically equivalent to a rem of any other type of radiation and a rad is the same amount of energy per gram for all types of radiation for any given material.

Table 8. Radiation Relationships

Radiation	r	rep	ren.	rad in			RBE
				air	muscle	water	
X-ray	1	1	1	.86	.97	.97	1
Gamma	1	1	1	.86	.97	.97	1
Beta	NA	1	1-2	.86	.97	.97	1-2
Proton	NA	1	5	.86	.97	.97	5
Alpha	NA	1	10-20	.86	.97	.97	10-20
Fast neutrons	NA	1	10	.86	.97	.97	10
Slow neutrons	NA	1	4-5	.86	.97	.97	4-5

The conversion factors between air, muscle, and water should not be taken too seriously, as the values vary with different energy particles or waves of the same radiation.

#### 156 PROBLEMS

a. If the weekly permissible total body absorption dose is 0.3 rem, what is the weekly permissible dose in rad for:

- (1) X-rays
- (2)  $\gamma$  rays
- (3)  $\beta$  particles
- (4) Slow neutrons
- (5) Fast neutrons

(Use Table 8).

#### 157 RADIATION DOSES AND EFFECTS

a. There are two kinds of doses, radiation exposure dose and radiation absorption dose. The first is usually measured in roentgens and the second in rads. In health physics we are interested in the interaction of radiation with the living organism; so the amount of

radiation absorbed by the organism is more important than the amount to which the organism is exposed. In other words radiation must react with the body in order to produce a biological effect. The degree of interaction of radiation with living matter will vary with the circumstance such as parts of the body involved, how fast the dose is received, and the type of radiation. For the same exposure dose, the absorption dose will vary from soft tissue to bone.

Note that the mass of tissue involved must be specified in order to determine the effect of the dose received. If one finger receives 1000 rad, the effect on the system will be much less than exposure of the whole body to 1000 rad.

b. Dose rate is the dose received per unit time. It may be expressed as exposure dose rate in r/hour or absorption dose rate in rad/hour. Of course different units of time or dose might be used. Other expressions for dose rate which might be used are milliroentgens/hour, roentgens/day, rem/hour, etc.

c. Dosage is the summation of doses received over a period of time. For example, a given operation may result in the operator receiving a whole-body dose of 0.01 r. If the operation is performed 15 times a day, the daily dosage will be 0.15r; and the dosage per 5-day work week will be 0.75 r.

d. Measurement. Biological injury from radiation exposure depends upon the amount of tissue ionized; hence, a good survey meter should indicate a response proportional to the tissue ionization produced. Ionization chamber instruments can be designed to give the proper response over a wide energy range, and quantitative surveys must, in general, be made with such instruments. Geiger-Muller counters respond to the amount rather than ionizing power of any incident radiation. For example, 100 beta particles of 0.15 Mev energy from C-14 would produce the same Geiger-Muller counter response as 100 beta particles of 3.5 Mev energy from K-42 despite the fact that the latter have about 25 times more ionizing power than the former. Unless specially calibrated, a Geiger-Mueller counter should be considered a sensitive radiation detector rather than an instrument capable of quantitative measurement.

e. Effects. In establishing limits for exposure to radiation, situations which have produced known injuries must be evaluated. Many cases of radiation injury have occurred unfortunately, but equally unfortunate is that in most of these cases no accurate tissue dose data were obtained. Therefore, any figures for permissible exposures are subject to modification as more information is obtained. The permissible whole-body radiation dose is 0.3 r per week in the United

States. Higher exposures are permitted under unusual circumstances, provided the whole-body dose for any 2-week period does not exceed 0.6 r. Future military operations in time of war might, of course, require exposure to doses considerably in excess of this limit. There are undoubtedly very wide variations in individual sensitivity to radiation. Unfortunately, little quantitative information is available.

f. An overexposure to radiation is usually first indicated by a drop in the white cell count of the blood. This drop is proportional to the dose received. The white count is a function of general body condition, of course, and only a persistent low count or a pronounced low count following known radiation exposure should be viewed with great concern. A drop in the red cell count in the blood may also occur. Unfortunately, this effect is somewhat latent and may not be detected for several days even after severe overexposure.

g. Effects of radiation on skin tissue are manifested in such symptoms as ulcers of the mouth, throat, and intestines. These hemorrhage in time and cause bleeding gums, vomiting, bloody diarrhea, etc. Later, pinpoint and blotchy hemorrhages appear in the skin, and loss of hair occurs.

h. The effect of radiation exposures slightly above tolerance at intervals over a considerable length of time can be various anemias and blood damage, bone damage, kidney damage, liver damage, and tumor formations. These effects will not be discussed extensively in this text.

i. External alpha-particle bombardment has no biological effect because most of the particles are absorbed in the dead layers of skin. Beta particles, however, can penetrate the dead layer of skin. Very energetic beta particles can penetrate up to 3 centimeters of tissue. The effects of beta overexposure are almost entirely surface in nature and appear as burns whose severity is determined by the extent of the overexposure. Neutrons can penetrate up to 10 centimeters of tissue. Few human organs therefore are safe from neutron damage. It has been pointed out previously that neutrons produce alpha particles or protons (primarily scattered protons); hence, the effects will correspond to those associated with internal alpha exposure, which is very dangerous. Strict isolation of the effects due to neutron exposure is difficult because large neutron doses are commonly accompanied by large doses of gamma radiation and the biological effects are intermingled. In addition to the damage from primary ionization, a very intense neutron exposure can produce radioactive isotopes in the body.

j. Tolerances. It is almost universally accepted in the United States that 0.3 r per week is the maximum whole-body dose capable of being indefinitely sustained without harmful effects. Any revision of this limit would probably be downward. A dose of 0.0001 r per day from cosmic radiation alone is experienced at sea level. This dose increases to 0.3 r per day at 40,000 feet, the increase being due to low radiation attenuation by the rarefied atmosphere at high altitudes.

k. The 5-percent lethal dose (LD-5) is that dose at which essentially 5 percent of those exposed will be fatalities within a short period of time. The accepted figure for this value is 150 r received in a short time interval. The 50-percent lethal dose (LD-50) is considered to be 450 r received in a short time interval. The 100-percent lethal dose (LD-100) is a somewhat nebulous figure since it is unlikely that any dose will definitely kill all those exposed. It is probable, however, that a dose of 600 r received in a short time interval will kill 999 out of 1000 people. The mean lethal dose is that dose at which those exposed have a survival probability of  $1-1/e$  or about 63 percent. This dose for humans is probably about 380 r received in a short period of time. (Recent investigations indicate that the actual LD-50 might be 645 r with the LD-100 increased accordingly.)

l. The Los Alamos Scientific Laboratory has established the following whole-body neutron tolerances for a 40-hour work week:

<u>Neutron Energy</u>	<u>Flux, in neutrons per square centimeter per second</u>
Thermal	2000
100 ev	1550
$5 \times 10^3$ ev	1700
$2 \times 10^4$ ev	850
0.1 Mev	250
0.5 Mev	90
1.0 Mev	55
2.5 Mev	60
5.0 Mev	55
7.5 Mev	50
10 Mev	50
10 to 30 Mev	30

The lethal whole-body neutron dose is considered to be  $10^{11}$  neutrons per square centimeter received within a few days.

m. Medical treatment or examination involving a single X-ray picture exposes the body to doses of 0.1 r to 3 r. Fluoroscopic examinations expose the body to doses up to 30 r.

n. Uranium handling tolerances are based primarily on beta emission from the uranium daughter products. The natural uranium tolerance for direct hand contact is 6 hours per week. The tolerance is increased to 12 hours per week by the use of gloves 1 millimeter thick. The handling tolerance for uranium enriched to nearly 100 percent uranium-235 is about 16 hours per week. The increased tolerance compared to the natural uranium tolerance is attributable to the lesser beta activity of the daughter products.

o. The tolerance for handling uncoated plutonium with drybox gloves is 3.4 hours per week. When the plutonium is nickel-coated the handling tolerance with bare hands becomes 4.3 hours per week.

p. One curie of polonium emits gamma radiation of about 65 milliroentgens per hour at a distance of 1 centimeter. The artificially produced polonium is normally processed to remove impurities, particularly oxygen, and thereby to lower the neutron activity to less than 100 neutrons per second per curie. If exposed to air, the neutron activity of the polonium may rise to as much as 2800 neutrons per second per curie. When combined with beryllium, the mixture emits gamma radiation of about 1.1 r per hour at a distance of 1 centimeter.

## 158 INTERNAL RADIATION HAZARDS

a. Many factors influence the hazard presented by radioactive materials which become lodged within the body. Such factors as activity (half life), types of radiation emitted, location in the body, and duration of internal exposure, are typical.

b. Radioactive materials may enter the body by inhalation, ingestion, or directly through breaks in the skin. Once within the body, the chemical nature of the substance determines its disposition. Some materials are rapidly eliminated in the body wastes. Others, such as radium and plutonium, are bone seekers and are, therefore, very difficult to dislodge. Uranium lodges in such organs as the kidneys. Tritium, being a hydrogen isotope, becomes distributed throughout the body.

c. Short isotopic half lives indicate high radioactivity. In general, then, materials with short half lives present internal hazards proportionately greater per unit mass than those presented by materials with long half lives.



d. Because the bodily processes include complex and extensive chemical activities, every substance entering the body has a definite probability of being eliminated. This probability is reflected in the quantity called metabolic half life, which is the length of time necessary for elimination from the body of one-half of any contained radioactive substance. The elimination process is an exponential one (i. e., amount of material in body varies exponentially with time).

e. A radioactive substance within the body is dissipated by two means: radioactive decay and physiological elimination. These processes have discrete half lives. Their combined effect is represented in a new value called biological half life, which is less than that of either eliminative process. The following mathematical expressions apply:

Let  $t_{1/2} \text{ (rad)} = \text{radiological half life}$

$t_{1/2} \text{ (met)} = \text{metabolic half life}$

$t_{1/2} \text{ (biol)} = \text{biological half life}$

$$\lambda \text{ (rad)} = \frac{0.693}{t_{1/2} \text{ (rad)}}$$

$$\lambda \text{ (met)} = \frac{0.693}{t_{1/2} \text{ (met)}}$$

$$\lambda \text{ (biol)} = \frac{0.693}{t_{1/2} \text{ (biol)}} \text{ where } \lambda \text{'s are decay constants}$$

$$\frac{1}{t_{1/2} \text{ (biol)}} = \frac{1}{t_{1/2} \text{ (rad)}} + \frac{1}{t_{1/2} \text{ (met)}}$$

f. While alpha particle emitters external to the body are essentially harmless, internally their intense tissue ionization is very hazardous. Beta particle emitters constitute roughly the same hazard whether situated externally or internally. Tissue ionization from contained gamma emitters is very sparse; and therefore, it is seldom felt necessary to consider gamma emission in the calculation of internal tolerances. General levels of maximum permissible concentrations (MPC) considered safe for any radioactive isotope except strontium-90, plutonium-239, or radium-226 are given below. These are only indications, and levels applicable to a given organization should be obtained from applicable regulations.

<u>Media</u>	<u>Beta-Gamma Emitter</u>	<u>Alpha Emitter</u>
Air	$2.22 \times 10^3 \text{ d/m/m}^3$	$11.1 \text{ d/m/m}^3$
Water	222 d/m/l	222 d/m/l

d/m/m<sup>3</sup>: disintegrations per minute per cubic meter.  
d/m/l: disintegrations per minute per liter.

Specific isotopic tolerances are presented in table 8.

These are, again, just indications of permissible concentrations, and appropriate authority should be consulted for a specific organization.

Table 8. Maximum Permissible Concentrations of Various Radioactive Isotopes in Water and Air<sup>1</sup>

	<u>Air - d/m/m<sup>3</sup></u>	<u>Water - d/m/l</u>
Cobalt-60	$7.7 \times 10^5$	$9 \times 10^6$
Tritium	$1.48 \times 10^7$	$1.48 \times 10^8$
Plutonium-239	4.44 (insoluble) 4.44 (soluble)	NA $3.33 \times 10^3$
Polonium-210	155 (insoluble) 444 (soluble)	NA $6.66 \times 10^4$
Inhalloy	37.7 (insoluble) 37.7 (soluble)	NA $1.55 \times 10^5$
Oralloy	35.5 (insoluble) 222 (soluble)	NA $3.33 \times 10^5$

g. The tolerance for ingested radioactive material is a function of the quantity of the material which will be absorbed through the walls of the gastrointestinal tract. This quantity depends upon the material, general body condition at the time of exposure, and many other factors.

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<sup>1</sup> It should be noted in comparing permissible concentrations that they are on an activity (disintegration per unit time) basis and not a mass basis.

It is necessary in establishing the tolerance to make a generous allowance for indeterminate variables.

h. Figures for maximum permissible air contamination are based upon the assumption that 75 percent of the material inhaled will be absorbed by tissues of the upper respiratory tract and only 25 percent will reach the lungs. This distribution would tend to minimize the quantity of material reaching the blood stream, but the material absorbed in the upper respiratory tract might badly damage those tissues.

i. Tritium, an isotope of hydrogen, has an atomic mass of three and is a low-energy beta emitter. It may enter the body through inhalation or absorption through the skin. It is thought that this material becomes distributed throughout the body. It has a biological half life of approximately 12 days, which can be reduced considerably by raising the fluid intake, and thereby increasing the volume eliminated.

#### 159. TREATMENT OF RADIATION SICKNESS

a. Treatment of radiation sickness can not achieve a cure in the same sense that treatment of a bacterial or virus infection can; that is, the cause is not removed. Treatment of the illness can be best directed toward minimizing the deleterious effects of dangerous exposure to radiation.

b. Whole-body transfusions are given to counteract the extensive blood damage from radiation. Antibiotics are administered to bolster body resistance, lowered by white blood cell destruction, to secondary infection. The victim may be fed intravenously to circumvent inability to eat or loss of appetite due to nausea, vomiting, ulcers in the mouth and throat, etc.

c. Much research has been devoted to the problem of discovering a chemical treatment to prevent radiation sickness. Although some encouraging results have been obtained, the problem is still far from solution.

#### 160. PERSONAL PROTECTIVE MEASURES

a. Personal Problems. Wide dissemination of correct information concerning the dangers of radiation would eliminate much of the needless worry due to misapprehension among the general public. Such worries as the supposed danger of permanent sterility from overexposure and possible high incidence of undesirable mutations

among the progeny of irradiated parents are typical.

b. **Protective Measures.** To limit external exposure, any one or all of the following measures may be taken:

(1) Remove the source of contamination. If the source is not being used, take it to a segregated storage place. Removal of contamination is much easier if proper precautions, such as covering the area with Kraft paper or painting the surface with "strippable" plastic paint, have been taken before the material becomes dispersed. Decontaminating an unprotected surface is primarily an abrasive process, scrubbing with a detergent and water, "hosing down" with high-pressure water or steam, using a complexing agent such as citric acid, or removing the surface with acid or by sandblasting. Each worker should be given protective clothing, which provides enough coverage to protect the worker as well as his personal clothing, and which can be washed in a laundry equipped to handle contaminated clothing and dispose of the contaminated wash water.

(2) Limit the amount of time spent in a radiation area. Determine the rate of exposure, and limit the amount of time the worker spends in that area to that which will give him only his permissible exposure. Each worker should be given personnel monitoring equipment to record the exposure which he will receive.

(3) Reduce the rate of exposure. Interposing shielding between the source and the worker or moving the worker farther from the source will reduce the rate of exposure to the worker. Lucite or glass can be used for beta shielding. Paraffin and water are acceptable for fast neutron attenuation. The internal exposure can be controlled only by preventing the entry of radioactive materials into the body. Respiratory protection for short periods in low concentrations of airborne contamination may be provided by respirators which filter the air to the mouth and nose. For higher concentrations (50 times the MPC), supplied air masks are recommended. Nose swipes taken at the end of a working period may be used as indicators of inhaled contamination. Eating and smoking should not be permitted in contaminated areas. Workers should be properly indoctrinated to use hand counters, to request surveys often when handling radioactive materials, and to report immediately all injuries where the skin is broken in order that any contamination may be removed with minimum absorption.

(4) The amount of material which has reached the interior of the body can be estimated by the quantity found in the body fluids. The urine is the most available body fluid. Whenever an internal

exposure is suspected, a urine specimen should be requested and analyzed as soon as possible. Radium, for example, quickly becomes fixed in the bone and can then only be detected by taking breath samples and counting them in a Radon Breath Counter.

c. Materials which are contaminated with short-lived isotopes can be stored until normal decay makes possible their disposal through usual channels. A segregated burying pit, plainly marked and surrounded by a high, strong fence, is used for disposal of waste contaminated with long-lived radioactive isotopes. All contaminated waste should be packaged in sealed containers and labelled for hauling to the dump. The vehicle used for hauling the waste should be of such construction that it can be decontaminated easily.

d. Natural radiation sources should be leak-tested whenever dropped, or when deterioration of the container is suspected, or at least once every 6 months. Polonium sources are especially dangerous because of the marked tendency of polonium to escape and spread.

# APPENDIX I

## SYMBOLS

<u>SYMBOL</u>	<u>MEANING</u>	<u>SPELLED</u>	<u>PRONOUNCED</u>
A	Mass number		
Z	Atomic number		
$\alpha, {}_2^4\text{He}$	Alpha particle Helium nucleus		
$\beta^-, {}_{-1}^0\text{e}$	Beta particle		
$\beta^+, {}_{+1}^0\text{e}$	Positive beta particle Positron		
$\gamma, {}_0^0\gamma$	Gamma radiation		
$\lambda$	Wavelength	Lambda	lām'da
$\nu$	Frequency	Nu	nū
$\eta, {}_0^0\eta$	Neutrino	Eta	ēta
h	Planck's constant		
k	Boltzmann's constant		
R	Rydberg's constant		
$\rho$	Density	Rho	rō
$\sigma$	Cross section	Sigma	sīg'ma
$\nu$	Neutrons per fission	Nu	nū
f	Productivity factor		
k	Multiplication or reproduction factor		

<u>SYMBOL</u>	<u>MEANING</u>	<u>SPELLED</u>	<u>PRONOUNCED</u>
<b>M</b>	<b>Multiplication</b>		
<b><math>m_e</math></b>	<b>Mass of electron</b>		
<b>n</b>	<b>Neutron</b>		

## APPENDIX II

### VALUES OF PHYSICAL CONSTANTS

<u>CONSTANT</u>	<u>SYMBOL AND VALUE</u>
Atomic mass unit	Amu = $1.67 \times 10^{-24}$ g = 931 Mev
Avogadro's number	N = $6.02 \times 10^{23}$ molecules/gram mol. wt.
Velocity of light	c = $3 \times 10^{10}$ cm/sec
Boltzmann's constant	k = $1.38 \times 10^{-16}$ erg/deg K.
Charge on the electron	e = $4.803 \times 10^{-10}$ esu
Planck's constant	h = $6.625 \times 10^{-27}$ erg-sec
Rydberg's constant	R = $109737 \text{ cm}^{-1}$
Base of natural logarithms	e = 2.7183
Electron rest mass	$m_e = 9.1 \times 10^{-28}$ g; 0.00055 amu
Proton rest mass	$m_p = 1.66 \times 10^{-24}$ g; 1.00758 amu
Neutron rest mass	$m_n = 1.67 \times 10^{-24}$ g; 1.00894 amu
Absolute zero	= $-273.16^\circ \text{ C.}$ ; $0^\circ \text{ K.}$



## **APPENDIX III**

### **USEFUL CONVERSIONS**

#### **LENGTH**

$$1 \text{ cm} = 0.394 \text{ in} = 10 \text{ mm}$$

$$1 \text{ in} = 2.54 \text{ cm}$$

$$1 \text{ meter} = 100 \text{ cm} = 10^6 \text{ microns} = 39.37 \text{ in}$$

$$1 \text{ micron} = 10^{-4} \text{ cm}$$

$$1 \text{ angstrom unit} = 10^{-8} \text{ cm}$$

#### **AREA**

$$1 \text{ cm}^2 = 0.155 \text{ in}^2$$

$$1 \text{ barn} = 1 \times 10^{-24} \text{ cm}^2$$

#### **VOLUME**

$$1 \text{ cm}^3 = 0.061 \text{ in}^3$$

$$1 \text{ liter} = 1000 \text{ cm}^3$$

#### **TIME**

$$1 \text{ sec} = 10^6 \text{ microseconds}$$

#### **MASS**

$$1 \text{ kg} = 2.2 \text{ lbs}$$

$$1 \text{ lb} = 453.6 \text{ g}$$

#### **PRESSURE**

$$1 \text{ atm} = 1033.2 \text{ g/cm}^2 = 14.7 \text{ lb/in}^2$$

#### WORK AND ENERGY

$$1 \text{ erg} = 1 \text{ dyne-cm} = 1 \times 10^{-7} \text{ joule} = 2.39 \times 10^{-8} \text{ cal}$$

$$1 \text{ joule} = 10^7 \text{ erg} = 2.778 \times 10^{-4} \text{ watt hours}$$

$$1 \text{ ev} = 1.6 \times 10^{-12} \text{ erg}$$

$$1 \text{ amu} = 931 \text{ Mev}$$

#### MISCELLANEOUS

$$1 \text{ curie} = 3.7 \times 10^{10} \text{ disintegrations/sec}$$

# APPENDIX IV TABLE OF ATOMIC MASSES

Z	ELEMENT	A	MASS	Z	ELEMENT	A	MASS	Z	ELEMENT	A	MASS
0	Electron	0	0.00055	19	Potassium	37	36.9630	51	Antimony	122	121.845
0	Neutron	1	1.00866			38	37.9795	52	Tellurium	124	123.844
1	Proton	1	1.00728			39	38.9747				
1	Hydrogen	1	1.00813			40	39.9760				
2	(Deuterium)	2	2.01471			41	40.9779				
3	(Tritium)	3	3.01702	20	Calcium	40	39.9753	53	Iodine	126	125.977
						42	41.9711	54	Xenon	128	127.936
2	Helium	3	3.01700			43	42.9723				
		4	4.00260			44	43.9723				
		6	6.0209	21	Scandium	45	44.9669	55	Cesium	132	131.846
3	Lithium	6	6.01697			46	45.9669	56	Barium	136	137.906
		7	7.01622			47	46.9669	57	Lanthanum	139	138.993
		8	8.02302	22	Titanium	48	47.9669	58	Cerium		
4	Beryllium	9	9.01216			49	48.9669	59	Praseodymium		
		10	10.01677			50	49.9669	60	Neodymium	145	144.982
5	Boron	10	10.01618			51	50.9669			146	145.982
		11	11.01284	23	Vanadium	51	50.9957			148	147.982
		12	12.0180			52	51.9957			150	149.984
6	Carbon	12	12.0100	24	Chromium	52	51.9966				
		13	13.00335			53	52.9966				
		14	14.00307			54	53.9966				
7	Nitrogen	14	14.00307			55	54.9966				
		15	15.00499	25	Manganese	55	54.9966				
		16	16.00608	26	Iron	56	55.9966				
8	Oxygen	16	16.00000			57	56.9966				
		17	17.00450			58	57.9966				
		18	18.00450			59	58.9966				
9	Fluorine	19	19.00199			60	59.9966				
		20	20.0063			61	60.9966				
10	Neon	20	20.0067			62	61.9966				
		21	21.00947			63	62.9966				
		22	22.00947			64	63.9966				
11	Sodium	23	22.98977			65	64.9966				
		24	24.00947			66	65.9966				
		25	25.00947			67	66.9966				
		26	26.00947			68	67.9966				
		27	27.00947			69	68.9966				
		28	28.00947			70	69.9966				
		29	29.00947			71	70.9966				
		30	30.00947			72	71.9966				
		31	31.00947			73	72.9966				
		32	32.00947			74	73.9966				
		33	33.00947			75	74.9966				



## APPENDIX V

### GENERAL ELECTRIC CHART OF THE NUCLIDES

All the necessary information for the use of this chart appears in the upper left corner of the rear of the chart. We shall note some of the more important items.

Each of the horizontal rows represents one element. The spaces in each row that are filled show the known isotopes of the element. Spaces shaded in gray represent isotopes which occur in nature and generally are considered stable. Actually, a few of these "stable" nuclides are radioactive but of very long half life; these are indicated by black rectangular areas within their spaces. The unshaded spaces represent radioactive isotopes; those with black rectangular areas show they are found in nature.

The space at the left end of each row, heavily bordered in black, gives properties of each element as a whole, including the chemical atomic weight.

In each of the other occupied spaces, there is shown first the symbol, followed by the mass number of the nuclide indicated. The mass number,  $A$ , is the number of nucleons in the nucleus.  $A - Z$  is thus the number of neutrons. This number is listed at the bottom of alternate columns.

Isobars lie in spaces placed diagonally from lower right to upper left.

For stable nuclei, abundance of the isotope is given. For radioactive nuclei, the emission, percentage of the various radiations, and their energies and half lives, are presented. A "Classification" letter appears before the symbol for each nuclide. The classification code appears under the column labeled "symbols." Some of the known isomeric states are indicated by a division of the space for the nuclide. Thermal neutron absorption cross sections are listed in ovals in nuclide spaces when such information is known and unclassified. A small black triangle in the lower right on a nuclide space indicates that this particular isotope may be a fission fragment.

Included on the back of the chart is coding for nuclear reactions. If the nuclear reaction and original nucleus is known, the product nucleus may be found. Displacements caused by nuclear reactions are also coded on the back of the chart.

**APPENDIX VI**  
**THE ELEMENTS**

<u>NAME</u>	<u>SYMBOL</u>	<u>ATOMIC NO.</u>
Actinium	Ac	89
Aluminum	Al	13
Americium	Am	95
Antimony	Sb	51
Argon	A	18
Arsenic	As	33
Astatine	At	85
Barium	Ba	56
Berkelium	Bk	97
Beryllium	Be	4
Bismuth	Bi	83
Boron	B	5
Bromine	Br	35
Cadmium	Cd	48
Calcium	Ca	20
Californium	Cf	98
Carbon	C	6
Cerium	Ce	58

<u>NAME</u>	<u>SYMBOL</u>	<u>ATOMIC NO.</u>
Cesium	Cs	55
Chlorine	Cl	17
Chromium	Cr	24
Cobalt	Co	27
Copper	Cu	29
Curium	Cm	96
Dysprosium	Dy	66
Erbium	Er	68
Europium	Eu	63
Fluorine	F	9
Francium	Fr	87
Gadolinium	Gd	64
Gallium	Ga	31
Germanium	Ge	32
Gold	Au	79
Hafnium	Hf	72
Helium	He	2
Holmium	Ho	67
Hydrogen	H	1
Indium	In	49
Iodine	I	53
Iridium	Ir	77



<u>NAME</u>	<u>SYMBOL</u>	<u>ATOMIC NO.</u>
Iron	Fe	26
Krypton	Kr	36
Lanthanum	La	57
Lead	Pb	82
Lithium	Li	3
Lutetium	Lu	71
Magnesium	Mg	12
Manganese	Mn	25
Mercury	Hg	80
Molybdenum	Mo	42
Neodymium	Nd	60
Neon	Ne	10
Neptunium	Np	93
Nickel	Ni	28
Niobium (Columbium)	Nb (Cb)	41
Nitrogen	N	7
Osmium	Os	76
Oxygen	O	8
Palladium	Pd	46
Phosphorus	P	15
Platinum	Pt	78
Plutonium	Pu	94

<u>NAME</u>	<u>SYMBOL</u>	<u>ATOMIC NO.</u>
Polonium	Po	84
Potassium	K	19
Praseodymium	Pr	59
Promethium	Pm	61
Protactinium	Pa	91
Radium	Ra	88
Radon (Emanation)	Rn (EM)	86
Rhenium	Re	75
Rhodium	Rh	45
Rubidium	Rb	37
Ruthenium	Ru	44
Samarium	Sm	62
Scandium	Sc	21
Selenium	Se	34
Silicon	Si	14
Silver	Ag	47
Sodium	Na	11
Strontium	Sr	38
Sulfur	S	16
Tantalum	Ta	73
Technetium	Tc	43
Tellurium	Te	52

<u>NAME</u>	<u>SYMBOL</u>	<u>ATOMIC NO.</u>
Terbium	Tb	65
Thallium	Tl	81
Thorium	Th	90
Thulium	Tm	69
Tin	Sn	50
Titanium	Ti	22
Tungsten	W	74
Uranium	U	92
Vanadium	V	23
Xenon	Xe	54
Ytterbium	Yb	70
Yttrium	Y	39
Zinc	Zn	30
Zirconium	Zr	40

## APPENDIX VII

### GLOSSARY

Absolute Zero--The temperature at which all thermal (molecular) motion ceases; zero point in the absolute temperature scale, equal to  $-273.18^{\circ}\text{C}$ . or  $-459.72^{\circ}\text{F}$ . Absolute temperature  $T$  is given by the equation:

$$\frac{1}{2} m v_{av}^2 = \frac{3}{2} kT.$$

Absorption--

1. The internal taking up of one material by another.
2. Transformation of radiant energy into other forms of energy when passing through a material substance.

Absorption Coefficient--The fractional decrease in intensity of a beam of radiation per unit thickness (linear absorption coefficient), per unit volume (mass absorption coefficient), or per atom (atomic absorption coefficient) of absorber.

Acceleration--The time rate of change of velocity in either magnitude or direction. CGS unit:  $\text{cm}/\text{sec}^2$ .

Acceleration Due to Gravity (g)--The acceleration of a freely falling body in a vacuum;  $980.665 \text{ cm}/\text{sec}^2$  or  $32.174 \text{ ft}/\text{sec}^2$  at sea level and  $45^{\circ}$  latitude.

Activation Energy--The energy necessary to start a particular reaction. Nuclear: The amount of outside energy which must be added to a nucleus to start a particular nuclear reaction. Chemical: The amount of outside energy necessary to activate an atom or molecule to cause it to react chemically.

Adsorption--The adhesion of one substance to the surface of another.

Alpha Particle--A helium nucleus, consisting of 2 protons and 2 neutrons, with a double positive charge. Its mass is 4.002764 amu (mass units)

Alpha Ray--A stream of fast-moving helium nuclei; a strongly ionizing and weakly penetrating radiation.

Alternating Current--An electric current (flow of electrons) which periodically reverses direction.

Ampere--The practical unit of current; that current which will deposit 0.001118 gm of silver in 1 sec; the flow of 1 coulomb/sec; the flow of  $3 \times 10^{19}$  electrons/second. Abbreviation: amp.

Amplification--As related to detection instruments, the process (either gas, electronic, or both) by which ionization effects are magnified to a degree suitable for their measurement.

Amplitude--The maximum value of the displacement in an oscillatory motion.

Angular Acceleration--The time rate of change of angular velocity either in angular speed or in the direction of the axis of rotation. CGS unit: radians/sec<sup>2</sup>.

Angular Velocity--The time rate of angular displacement about an axis. CGS unit: radians/sec. If the angle described in time  $t$  is  $\theta$ , the angular velocity is  $\omega = \frac{\theta}{t}$ , where  $\theta$  is in radians,  $t$  is in seconds, and  $\omega$  is in radians per second.

Angstrom Unit-- $10^{-8}$  cm, a convenient unit for measuring wavelength of light. Abbreviation: Å.

Atom--The smallest particle of an element which still retains all characteristics of the element.

Atomic Number--The number of protons in the nucleus, hence the number of positive charges on the nucleus. It is also the number of electrons outside the nucleus of a neutral atom. Symbol:  $Z$ .

Atomic Weight--The relative weight of the atom of an element compared with the weight of one atom of oxygen taken as 16; hence, a multiple of 1/16 the weight of an atom of oxygen.

Avogadro's Law--The hypothesis that equal volumes of all gases at the same pressure and temperature contain equal numbers of molecules. Hence the number of molecules contained in 1 cm<sup>3</sup> of any gas under standard conditions is a universal constant.

Avogadro's Number--The number of molecules in a gram-molecular weight of any substance ( $6.03 \times 10^{23}$  molecules); also, the number of atoms in a gram-atomic weight of any element.

Barn--The unit expressing the probability of a specific nuclear reaction taking place in terms of cross-sectional area. It is  $10^{-24}$  cm<sup>2</sup>. (See Cross Section.)

Beta Particle--A charged particle emitted from the nucleus and having a mass and charge equal in magnitude to those of the electron.

Beta Ray--A stream of beta particles, more penetrating but less ionizing than alpha rays; a stream of high-speed electrons.

Binding Energy--The energy represented by the difference in mass between the sum of the component parts and the actual mass of the nucleus.

Brownian Movement--The continuous agitation of the particles of a colloidal suspension caused by the thermal motion of the molecules of the surrounding medium.

Calorie--The amount of heat necessary to raise the temperature of 1 gm of water 1° C. (from 14.5° C. to 15.5° C.). Abbreviation: cal.

Centripetal Force--The force required to keep a moving mass traveling in a circular path. The force is directed toward the axis of the circular path.

Chain Reaction--Any chemical or nuclear process in which some of the products of the process are instrumental in the continuation or magnification of the process.

Chemical Compound--A pure substance composed of two or more elements combined in a fixed and definite proportion by weight.

Conservation of Energy--The principle that energy can neither be created nor destroyed, and therefore the total amount of energy in the universe is constant. This law of classical physics is modified for certain nuclear reactions. (See Conservation of Mass-Energy.)

Conservation of Mass-Energy--The principle that energy and mass are interchangeable in accordance with the equation  $E = mc^2$ ; where E is energy, m is mass, and c is velocity of light.

Coulomb's Law of Electrostatic Charges--The force of attraction or repulsion exerted between two electrostatic charges,  $Q_1$  and  $Q_2$ , a distance,  $s$ , apart separated by a medium of dielectric value,  $\epsilon$ , is given by the equation:

$$F = \frac{Q_1 Q_2}{\epsilon s^2}.$$

Critical Size--For fissionable material, the minimum amount of a material which will support a chain reaction.

Cross Section (Nuclear)--The area subtended by an atom or molecule for the probability of a reaction; that is, the reaction probability measured in units of area

Decay--The disintegration of the nucleus of an unstable element by the spontaneous emission of charged particles and/or photons.

Density--The mass per unit volume. CGS unit: gm/cm<sup>3</sup>

Deuterium--A heavy isotope of hydrogen having 1 proton and 1 neutron in the nucleus. Symbol: D or  ${}_1\text{H}^2$ .

Deuteron--The nucleus of a deuterium atom containing 1 proton and 1 neutron

Dyne--That unit of force which, when acting upon a mass of 1 gm, will produce an acceleration of 1 cm/sec<sup>2</sup>.

Electric Field Intensity--The magnitude of the intensity of an electric field at a particular point, equal to the force which would be exerted upon a unit positive charge placed in the field at that point. The direction of the electric field is the direction of this force.

Electron--A negatively charged particle which is a constituent of every atom. A unit of negative electricity equal to  $4.80 \times 10^{-10}$  esu. Its mass is 0.000548 mu.

Electron Volt--The amount of energy gained by an electron in passing through a potential difference of 1 volt.  $1 \text{ ev} = 1.6 \times 10^{-12}$  ergs. Abbreviation: ev.

Electrostatic Field--The region surrounding an electric charge in which another electric charge experiences a force.

Electrostatic Unit of Charge (Statcoulomb)--That quantity of electric charge which, when placed in a vacuum 1 cm distant from an equal and like charge, will repel it with a force of 1 dyne. Abbreviation: esu.

Element--A pure substance consisting of atoms of the same atomic number, which cannot be subdivided by ordinary chemical means.

Endoergic Reaction--A reaction which absorbs energy.

Energy--The capacity for doing work. Potential energy is the energy inherent in a body because of its position with reference to other bodies. Kinetic energy is the energy possessed by a mass because of its motion. CGS units:  $\text{gm-cm}^2/\text{sec}^2$ , or erg.

Erg--The unit of work done by a force of 1 dyne acting through a distance of 1 cm. The unit of energy which can exert a force of 1 dyne through a distance of 1 cm. CGS units: dyne-cm, or  $\text{gm-cm}^2/\text{sec}^2$

Exoergic Reaction--The reaction which liberates energy.

Fission. See Nuclear Fission.

Fission Products--The elements and/or particles produced by fission.

Force--The push or pull which tends to impart motion to a body at rest, or to increase or diminish the speed or change the direction of a body already in motion.

Frequency--The number of cycles, revolutions, or vibrations completed in a unit of time. CGS unit:  $\text{sec}^{-1}$ .

Fusion. See Nuclear Fusion.

Gamma Ray--A high-frequency electromagnetic radiation with a range of wavelength from  $10^{-9}$  to  $10^{-10}$  cm, emitted from the nucleus

Gram-Atomic Weight--The relative atomic weight of an element, expressed in grams.

Gram-Molecular Weight (Gram-Mole)--The relative molecular weight of a compound, expressed in grams.

Half Life--The time required for one-half of the atoms of the substance originally present to decay by radioactivity



Half Thickness--The thickness of absorbing material necessary to reduce the intensity of radiation by one-half.

Heat--The energy associated with a mass because of the random motions of its molecules.

Heavy Water--The popular name for water which is composed of 2 atoms of deuterium and 1 atom of oxygen.

Hydrogen Atom--The atom of lightest mass and simplest atomic and nuclear structure, consisting of 1 proton with 1 orbital electron. Its mass is 1.008123 mu

Intensity of Radiation--The amount of radiant energy emitted in a specified direction per unit time and per unit surface area.

Ion--An atomic particle, atom, or chemical radical (group of chemically combined atoms) bearing an electrical charge, either positive or negative, caused by an excess or deficiency of electrons.

Ionization--The act or result of any process by which a neutral atom or molecule acquires either a positive or a negative charge.

Ionization Potential--The potential necessary to separate 1 electron from an atom with the formation of an ion having 1 elementary charge.

Ionizing Event--An event in which an ion is produced.

Isobars--Elements having the same mass number but different atomic numbers.

Isotope--One of two or more forms of an element having the same atomic number (nuclear charge) and hence occupying the same position in the periodic table. All isotopes are identical in chemical behavior, but are distinguishable by small differences in atomic weight. The nuclei of all isotopes of a given element have the same number of protons but have different numbers of neutrons.

Joule--A unit of work or energy.  $1 \text{ joule} = 10^7 \text{ ergs}$

Kinetic Energy--The energy which a body possesses by virtue of its mass and velocity. The equation is:  $K.E. = 1/2 mv^2$

Mass--The quantity of matter. One of the fundamental dimensions

**Mass Number**--The number of nucleons in the nucleus of an atom.  
Symbol: A.

**Mass Unit**--A unit of mass based upon 1/16 the weight of an oxygen atom taken as 16.00000. Abbreviation: mu, or atomic mass unit, amu.

**Mean Free Path**--The average distance a particle moves between collisions. Abbreviation: mfp, symbol,  $\bar{l}$ .

**Meson**--A short-lived particle carrying a positive, negative, or zero charge, and having a variable mass in multiples of the mass of the electron. Also called mesotron.

**Metastable State**--An excited state of a nucleus which returns to the ground state by the emission of a gamma ray over a measurable half life.

**Mev**--The abbreviation for million electron volts. See Electron Volt.

**Molecule**--The ultimate unit quantity of a compound which can exist by itself and retain all the properties of the original substance.

**Molecular Weight**--The sum of the atomic weights of all the atoms in a molecule.

**Momentum**--The product of the mass of a body and its velocity. CGS unit: gm-cm/sec.

**Neutron**--An elementary nuclear particle with a mass approximately the same as that of a hydrogen atom and electrically neutral; a constituent of the atomic nucleus. Its mass is 1.00893 mu.

**Neutrino**--A particle with zero rest mass and zero charge, emitted to preserve spin, momentum, and energy in  $\beta$  decay and other processes.

**Nuclear Fission**--A special type of nuclear transformation characterized by the splitting of a nucleus into at least two other nuclei and the release of a relatively large amount of energy.

**Nuclear Fusion**--The act of coalescing two or more nuclei.

**Nucleon**--The common name for the constituent parts of the nucleus. At present applied to protons and neutrons, but will include any other particle that is found to exist in the nucleus.

**Nucleus**--The heavy central part of an atom in which most of the mass and the total positive electric charge are concentrated. The charge of the nucleus, an integral multiple  $Z$  of the charge of the proton, is the essential factor which distinguishes one element from another.  $Z$  is the atomic number.

**Nuclide**--A general term referring to all nuclear species--both stable (about 270) and unstable (about 500)--of the chemical elements, as distinguished from the two or more nuclear species of a single chemical element which are called isotopes.

**Packing Fraction**--The difference between the atomic weight in mass units and the mass number of an element divided by the mass number and multiplied by 10,000. It indicates nuclear stability. The smaller the packing fraction, the more stable the element.

**Photoelectric Effect**--The process by which a photon ejects an electron from its atom. All the energy of the photon is absorbed in ejecting the electron and in imparting kinetic energy to it.

**Photon**--A quantity of energy emitted in the form of electromagnetic radiation whose value is the product of its frequency and Planck's constant. The equation is:  $E = h\nu$ .

**Planck's Constant**--A natural constant of proportionality  $h$  relating the frequency of a quantum of energy to the total energy of the quantum;

$$h = \frac{E}{\nu} = 6.6 \times 10^{-27} \text{ erg-sec.}$$

**Positron**--A nuclear particle equal in mass to the electron and having an equal but opposite charge. Its mass is 0.000548 mu.

**Potential Difference**--The difference in potential between any two points in a circuit; the work required to carry a unit positive charge from one point to another.

**Power**--The time rate of doing work; the time rate of expenditure of energy.

**Pressure**--The perpendicular component of force applied to a unit area; the total force divided by total area. CGS unit: dyne/cm<sup>2</sup>.

**Primary Electron**--The electron ejected from an atom by an initial ionizing event, as caused by a photon or beta particle.

**Principal Quantum Number**--The number,  $n = 1, 2, 3, \dots$  which describes the basic state of an atomic system in quantum theory.

**Proton**--A nuclear particle with a positive electric charge equal numerically to the charge of the electron and having a mass of 1.007575 mu.

**Quantum**--A discrete quantity of radiative energy equal to the product of its frequency and Planck's constant. The equation is:  $E = h\nu$ .

**Quantum Level**--An energy level of an electron or of any atomic system, distinct from any other of its energy levels by discrete quantities dependent upon Planck's constant.

**Quantum Mechanics**--The science of description of atomic systems in terms of discrete quantum states.

**Quantum Number**--One of a set of integral or half-integral numbers, one for each degree of freedom, which determines the state of an atomic system in terms of the constants of nature.

**Quantum State**--A term defining the way in which an atomic system exists at any specific time. This state is often described by means of a complex mathematical function. See Quantum Level.

**Quantum Theory**--The concept that energy is radiated intermittently in units of definite magnitude called quanta.

**Radiation**--A method of transmission of energy. Specifically:

1. Any electromagnetic wave (quantum).
2. Any moving electron or nuclear particle, charged or uncharged, emitted by a radioactive substance.

**Radioactivity**--The process whereby certain nuclides undergo spontaneous atomic disintegration in which energy is liberated, generally resulting in the formation of new nuclides. The process is accompanied by the emission of one or more types of radiation, such as alpha particles, beta particles, and gamma radiation.

**Reaction**--Any process involving a chemical or nuclear change.

**Roentgen**--The quantity of X or  $\gamma$  radiation which produces 1 esu of positive or negative electricity/cm<sup>3</sup> of air at standard temperature and pressure or  $2.083 \times 10^9$  ion pairs/cm<sup>3</sup> of dry air.

**Speed**--The time rate of displacement; distance moved per unit time.  
CGS unit: cm/sec.

**Spin**--The inherent, intrinsic angular momentum of an atomic particle; a quantum number in modern atomic theory.

**Temperature**--A measure of the degree of heat, or the intensity of heating, of an object.

**Valence**--The number representing the combining or displacing power of an atom; number of electrons lost, gained, or shared by an atom in a compound; the number of hydrogen atoms with which an atom will combine, or the number it will displace.

**Valence Electron**--Any electron which is gained, lost, or shared in a chemical reaction. Usually valence electrons are the outermost electrons in the atom.

**Velocity**--The time rate of displacement in a fixed direction. CGS unit: cm/sec.

**Velocity of a Wave**--The velocity of propagation in terms of wavelength  $\lambda$  and period T, or frequency  $\nu$ . The equation is:

$$v = \frac{\lambda}{T} = \nu\lambda.$$

**Wavelength**--The linear distance between any two similar points of two consecutive waves.

**Wave Motion**--The progressive disturbance propagated in a medium by periodic vibration of the particles of the medium. **Transverse wave motion** is that in which the vibration of the particles is perpendicular to the direction of propagation. **Longitudinal wave motion** is that in which the vibration of the particles is parallel to the direction of propagation.

**Weight**--The force with which a body is attracted toward the earth. CGS units: gm-cm/sec<sup>2</sup>.

**Work**--The transfer of energy by the application of a force through a distance. Product of a force and the distance through which it moves. CGS units: gm-cm<sup>2</sup>/sec<sup>2</sup>.

## APPENDIX VIII

### ANSWERS TO PROBLEMS

#### Paragraph 3e

(1)  $T = \frac{2E}{3k}$

(2)  $v = \sqrt{\frac{2E}{m}}$

(3)  $T = \frac{mv^2}{3k}$

(4) 3

(5)  $\frac{c-b}{a}$

#### Paragraph 10

a. 1215

b. 6950

c. 0.0161

d. 15.6

e. 165.6

f. 1730

g. 52.6

h. 6.05

i. 0.00744

#### Paragraph 10 (cont'd)

j. 53.0

k. 60.3

l. 0.0166

m. 0.887

n. 0.733

o. 0.000139

p. 158

#### Paragraph 18

a.  $4.9 \times 10^4$  dynes

b.  $1.43 \times 10^3$  c.n./sec<sup>2</sup>

c. 30 cm/sec<sup>2</sup>,  $1.80 \times 10^3$  dynes

d.  $2 \times 10^3$  gms

#### Paragraph 22

a.  $10^8$  ergs

$10^8$  ergs

b.  $5 \times 10^{13}$  watts

#### Paragraph 29

$1.95 \times 10^5$  cm/sec

Paragraph 35

- a.  $1.6 \times 10^{-6}$  ergs  
b.  $2.3 \times 10^{-3}$  dynes  
 $2.3 \times 10^{-11}$  ergs  
c.  $2.3 \times 10^5$  dynes  
 $2.3 \times 10^{-7}$  ergs

Paragraph 43

- a. 100 cps  
b.  $2 \times 10^4$  cm  
2 cm  
c.  $9.9 \times 10^{-17}$  ergs  
 $3.3 \times 10^{-12}$  ergs

- d.  $2 \times 10^{-5}$  cm

Ultraviolet

- e.  $2.42 \times 10^{14}$  cps  
 $1.24 \times 10^{-4}$  cm

Infrared

- f.  $1.98 \times 10^{-6}$  ergs  
 $3 \times 10^{20}$  cps

Gamma

Paragraph 61

- a.  $1.34 \times 10^{23}$   
b.  $1.20 \times 10^{24}$

Paragraph 61 (cont'd)

- $6.0 \times 10^{23}$   
 $1.67 \times 10^{-24}$  gm  
 $6.0 \times 10^{23}$   
 $3.33 \times 10^{-24}$  gm

- c.  $1.49 \times 10^4$  gms

Paragraph 69

- a. 376 gm  
 $1.085 \times 10^{24}$   
 $9.00 \times 10^{25}$   
b.  $6.02 \times 10^{22}$   
 $7.81 \times 10^{23}$   
c.  $6.60 \times 10^{-5}$  cm

Visible

Paragraph 77

a. Isotope	Isobar
$^{124}_{50}\text{Sn}$	$^{124}_{52}\text{Te}$
$^{122}_{50}\text{Sn}$	$^{122}_{52}\text{Te}$
$^{120}_{50}\text{Sn}$	$^{120}_{52}\text{Te}$
$^{116}_{50}\text{Sn}$	$^{116}_{48}\text{Cd}$
$^{114}_{50}\text{Sn}$	$^{114}_{48}\text{Cd}$
$^{112}_{50}\text{Sn}$	$^{112}_{48}\text{Cd}$
$^{119}_{50}\text{Sn}$	

Paragraph 77 (cont'd)

$^{118}_{50}\text{Sn}$

$^{117}_{50}\text{Sn}$

$^{115}_{50}\text{Sn}$

b. 1, 1.3, 1.43, 1.58

Paragraph 92

a. (1) 92 Mev

(2) 1614 Mev

(3) 1781 Mev

b. (1) 7.66 Mev/nucleon

(2) 7.80 Mev/nucleon

(3) 7.59 Mev/nucleon

Paragraph 105

a.  $\beta^-$

b. 13.5 curies

518 days

c. (1)  $1.382 \times 10^{-11}$  sec

(2) 0.006 grams

d. (1)  $^{236}_{92}\text{U}$

(2)  $^{220}_{86}\text{Rn}$

Paragraph 123

a. (1)  $^{18}_9\text{F}$

(2)  $^{17}_8\text{O}$

b. 5.74 Mev

Paragraph 123 (cont'd)

c. 18.6 Kev

d. 0.1 barn

e. 206 cm

Paragraph 130

a. 600 barns

b. 44.8 barns

Paragraph 140

206 Mev

Paragraph 156

a. (1) 0.3 rad

(2) 0.3 rad

(3) 0.15 to 0.30 rad

(4) 0.06 to 0.075 rad

(5) 0.03 rad



## NOTES

## INDEX

### A

Absolute zero, 19  
 Absorption nomogram, 122  
 Absorption of gamma, 119ff  
 Actinium series, 106f  
 Alpha biology, 177  
 Alpha decay, 89ff  
 Alpha interaction, 109f  
 Alpha ionization, 178  
 Alpha particle, 67  
 Alpha radiation, 87ff  
 Alpha RBE, 183  
 Amu, 41  
 Annihilation, 75, 117f  
 Artificial radioactivity, 97  
 Atom, definition, 21, 45  
 Atoms, 44ff  
 Atomic mass number, 64  
 Atomic mass unit, 41  
 Atomic number, 64  
 Atomic structure, 43ff  
 Avogadro's number, 45ff

### B

Balmer series, 56  
 Barn, 135  
 Becquerel, 86  
 Beta biology, 177  
 Beta decay, 71, 91ff  
 Beta interaction, 111ff  
 Beta ionization, 178  
 Beta particle, 67  
 Beta radiation, 87ff  
 Beta RBE, 183  
 Binding energy calculations, 80ff  
 Binding energy definition, 79  
 Binding energy per nucleon, 81ff, 149  
 Biological half life, 188  
 Bohr atom, 51ff  
 Bremsstrahlung, 113  
 Brownian movement, 21, 44f

### C

Calorie, 20  
 Capture reaction, 126f  
 Cell composition, 179f  
 Centigrade scale, 19  
 Chain reaction, 165ff  
 Chain reaction kinetics, 174ff  
 Characteristic, logarithmic, 7f  
 Charges, 25ff  
 Chemical reactions, 45  
 Compound, 45  
 Compound nucleus, 130  
 Compton effect, 116  
 Criticality, 167ff  
 Critical mass, 167  
 Cross section, 134ff, 142f  
 Cross sections, fission, 170f  
 Cross sections, fusion, 164  
 Cross sections, thermal neutron, 158  
 Curie, 98

### D

DD reaction, 160ff  
 DT reaction, 160  
 "Daughter", 105  
 Daughter nucleus, 128  
 Decay (see type of)  
 Decay constant, 97  
 Decay laws, 97ff  
 Decay nomogram, 102  
 Decay series, 101ff  
 Deflection experiment, 88  
 Delayed neutrons, 156  
 Detectors, neutron, 146  
 Deuteron, 75  
 Dimensions, 36ff  
 Discrete energies, alpha, 89  
 Discrete energies, gamma, 95  
 Discrete spectra, 51  
 Dosage, radiation, 183f  
 Dose rate, 183f

## INDEX (Continued)

### E

Ejected particle, 124  
 Ejected, 126f  
 Elastic scatter, 125f  
 Electricity, 25ff  
 Electrons, 25  
 Electrons, capture, 94  
 Electron volt, 41  
 Electromagnetic energy, 39f  
 Electromagnetic radiation, 28ff  
 Electromagnetic spectrum, 32f  
 Electromagnetic waves, 29ff  
 Electrostatic forces, 25ff  
 Electrostatic unit, 25  
 Element, definition, 21, 45  
 Energy, binding, 80ff  
 Energy, electromagnetic, 39f  
 Energy, electron volt, 41  
 Energy, excitation, 153  
 Energy, fission, 157  
 Energy, fusion, 160ff  
 Energy, kinetic, 17, 38f  
 Energy level diagram, 54f  
 Energy levels, orbital, 52ff  
 Energy, mass, 39, 41  
 Energy, neutron, 138f  
 Energy, nuclear, 67f  
 Energy, potential, 18  
 Energy, principles, 17f  
 Energy, reaction, 132ff  
 Energy, release calculation, 83ff  
 Energy, released, 132ff  
 Equations, algebraic, 2ff  
 Esu, 25  
 Ev, 27  
 Ev, 41  
 Excitation energy, 153  
 Exponents, 5ff

### F

F-factor, 171  
 Fahrenheit scale, 19

Fast neutron reactions, 142  
 Fast neutrons, 139  
 Fission chain reactions, 165ff  
 Fission energy, 157  
 Fission fragments, 150, 153ff  
 Fission-fusion comparison, 164  
 Fission neutrons, 154ff  
 Fission, principles, 82f, 148ff  
 Fission probability, 158  
 Fission reaction, 127, 140, 142  
 Forces, around nucleus, 124f  
 Forces, charge, 25ff  
 Forces, electrical, 73f  
 Forces, nuclear, 66f  
 Forces, principles, 13, 37f  
 Formulas algebraic, 2ff  
 Frequency, wave, 31  
 Fusion cross sections, 164  
 Fusion energy, 160  
 Fusion-fission comparison, 164  
 Fusion, principles, 83, 159ff  
 Fusion probability, 162ff

### G

Gamma absorption, 119f  
 Gamma absorption nomogram, 122  
 Gamma biology, 177ff  
 Gamma decay, 95f  
 Gamma interaction, 114ff  
 Gamma ionization, 178  
 Gamma radiation, 87ff  
 Gamma ray, 67, 75  
 Gamma RBE, 183  
 Gram molecular weight, 46f

### H

Half life, 100  
 Half life, biological, 188  
 Half life, metabolic, 188  
 Half thickness, 120f  
 Half thickness of materials, 121  
 Health physics, 177ff

## INDEX (Continued)

Heat, 19f  
Heat, specific, 20  
Human body, 178ff

### I

Ionization, 89, 108f  
Ionization, specific, 109  
Ionization, table of relative, 178  
Ion pair, 89, 109  
Ions, 108f  
Incident particle, 124  
Index of refraction, 30  
Inelastic scatter, 125f  
Interaction (see type), 108ff  
Intermediate neutrons, 139  
Internal radiation hazards, 187ff  
Isobars, 64ff  
Isomeric state, 68  
Isomeric transitions, 65  
Isomers, 64ff  
Isotopes, 64ff

### K

K-factor, 166  
Kelvin scale, 19  
Kinetic energy, principles, 38f  
Kinetic theory, 20ff

### L

Liquid drop theory, 152  
Logarithms, 5ff

### M

Magnetic effects, 28  
Mantissa, logarithmic, 7f  
Mass absorption coefficient, 120  
Mass defect, 79f  
Mass energy, 39, 41  
Mass per nucleon, 84  
Mass, principles, 12ff

Maxwellian distribution, 22ff  
Mean free path, 136  
Mendeljeef's chart, 47ff  
Meson theory, 73  
Metabolic half life, 188  
Metabolism, 179  
Metric system, 37  
Mev, 41  
Mixture, definition, 45  
Moderation, 145f  
Molecular motion, 20  
Molecule, definition, 21, 45  
Momentum, electromagnetic, 40  
Momentum, principles, 15  
Multiplication factor, 166, 173f  
Multiplying chain reaction, 166

### N

N to p ratio, 68ff  
N to p ratio curve, 70  
Negative numbers, 4f  
Neptunium series, 107  
Neutrino, 74f, 93  
Neutron biology, 177  
Neutron decay, 95  
Neutron detectors, 146  
Neutron energies, 138f  
Neutron induced radioactivity, 140f  
Neutron fission, 165ff  
Neutron mass, 138  
Neutron population, 168  
Neutron reactions, 137, 140f  
Neutron RBE, 183  
Neutron sources, 139f  
Neutrons, 64, 68ff, 73  
Neutrons, energies, 138f  
Neutrons, fast, 139  
Neutrons from fission, 154ff  
Neutrons, intermediate, 139  
Neutrons, reactions, 140f  
Neutrons, slow, 139  
Neutrons, thermal, 139  
Nuclear energy, 67f

## INDEX (Continued)

- Nuclear forces, 66f  
Nuclear reaction nomenclature, 127ff  
Nuclear reactions, 124ff  
Nuclear stability, 68ff, 96  
Nonsustaining chain reaction, 168
- O
- Orbits, 52ff
- P
- Pair production, 73ff, 116ff  
"Parent", 105  
Parent nucleus, 128  
Particles, chart, 76f  
Particles, elementary, 74  
Pauli exclusion principle, 59ff  
Periodic table, 49  
Periodic table, principles, 47ff  
Period, wave, 32  
Photoelectric effect, 115  
Photo-fission, 151  
Photons, 34, 39  
Pi, 1f  
Pile, nuclear, 140  
Planck's constant, 34, 39, 78  
Positron, 67  
Positron emission, 94  
Potential, electrical, 27  
Power, principles, 16f  
Productivity factor, 171  
Prompt neutrons, 156  
Protons, 64, 68ff, 73  
Proton biology, 178  
Proton ionization, 178  
Proton RBE, 183
- Q
- Quanta, light, 39  
Quantization, 52ff  
Quantum jumps, 52  
Quantum mechanics, 58f  
Quantum numbers, 58f  
Quantum theory, 51ff
- R
- Radiation damage to body, 179, 184f  
Radiation deflection, 88  
Radiation dosage, 183f  
Radiation effects, 179, 184ff  
Radiation ranges, 177f  
Radiation tolerances, 186f  
Radiation, treatment for, 190ff  
Radiation units, 180ff  
Radioactive emitters, 188ff  
Radioactive materials, 87  
Radioactivity, 86ff  
Radioactivity, artificial, 97  
Radioactivity, natural, 86ff  
RBE, 183  
Reaction energy, 132ff  
Reactions, neutron, 137, 140f  
Reaction nomenclature, 127ff  
Reaction probability, 134ff  
Reactor, 140  
Recoil nucleus, 124  
Relative Biological Effect, 182  
REM, 181  
REP, 181  
Resonance, 137  
Resonance reactions, 143ff  
Roentgen, 180  
Roentgen Equivalent Physical, 181  
Roentgen Equivalent Man, 181  
Rutherford atom, 48ff  
Rydberg constant, 55
- S
- Scatter, elastic, 125f  
Scatter, inelastic, 125f  
Slide rule use, 9ff  
Slow neutrons, 139

## INDEX (Continued)

Specific heat, 20  
Specific ionization, 109  
Spectral lines, 57  
Spectrography, 51  
Spectrum, electromagnetic, 32f  
Speed of light, 30  
Spin, angular momentum, 57ff  
Spontaneous fission, 158  
Stability, nuclear, 68ff, 96  
Stat volt, principles, 27  
Sustaining chain reaction, 166  
Symbols, algebraic, 1f

### T

Target nucleus, 124  
Temperature, 19f  
Temperature, velocity distribution, 23f  
Thermal neutrons, 139  
Thermal neutron cross sections, 158  
Thermal neutron fission, 150  
Thermal neutron reactions, 140f  
Thermonuclear reactions, 159ff, 163  
Thorium series, 105  
Threshold energy, 132  
Triton, 75  
Tunneling, 90, 162ff

### U

Units, summary, 42  
Uranium series, 103ff

### V

Valence, 45  
Volt, principles, 27

### W

Wavelength, 31ff, 39f

Wavelength, reciprocal, 32  
Wave mechanics, 90  
Wave-particle dualism, 78  
Waves, electromagnetic, 29ff  
Waves, longitudinal, 30  
Waves, transverse, 29ff  
Weight, principles, 13f  
Work, principles, 16f, 38

### Z

Zeeman and Stark effects, 57